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MEASUREMENTS OF FOLDED BEDS.[1]

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PAGE.

Introduction 367
Elements in the measurement of folded beds..... 369
(*a*) The true dip of the beds 369
(*b*) Measurements of distance 370
(*c*) Measurements of difference in elevation 370
(*d*) Assumptions concerning manner of folding 371
Calculation of thickness of folded beds 373
Comparison of Hayes' method and parallel folding 378
Effect of errors in observations of dip 379
Measurement of width of outcrop 381
Measurement of inclined beds in detail 382
Conclusion 384

INTRODUCTION.

In the study of many problems of structural geology, graphic methods commonly yield results that are sufficiently accurate for the purposes at hand and they are therefore widely used. With the development of interest in more accurate results, however, it is necessary to turn to mathematical calculations and formulæ, and their use in applied geology appears to be increasing. Formulæ have the further advantage that they permit an analysis of the relative importance of each of the elements that enters into a problem.

The determination of the thickness of a group of superimposed

[1] Published with the permission of the Director, U. S. Geological Survey.

beds is relatively simple where a vertical cross-section is well exposed. Where isolated exposures not too remote have similar strike and dip, the determination of the thickness of the beds is also simple. Where, however, isolated exposures have similar strike and different dip, the determination of the thickness of beds between them depends upon the assumptions that are made concerning their relations.

The general treatises on geology, such as those of Dana, A. Geikie, J. Geikie, Chamberlin and Salisbury, Pirsson and Schuchert, De Lapparent, Haug and Kayser only discuss the simplest conditions of inclined beds. Green[2] presents an interesting discussion of the methods of determining thickness between outcrops that are parallel and normal to the line joining them, as well as the case where the outcrops are parallel, but oblique to the line joining them. Lahee[3] discusses the conditions of folding, the construction of cross-sections and presents a table showing thickness between beds of similar dip, but does not discuss the case of different dip. Probably the method that is most widely used to calculate the thickness of beds between outcrops of different dip, is the graphic method described by Hayes.[4] Another graphic method for the same conditions is based upon the assumption that the outcrops are parts of concentric beds (parallel folds). Both of these graphic methods are open to the objection that (1) they take undue time for accurate preparation, (2) they do not yield accurate results where the difference in dip is 5° or less, (3) they do not make proper use of the accurate data that are now generally available by the use of plane-table methods of surveying.

The widespread use of structure contour maps in the study of the structure of oil fields is placing considerable value on accuracy of the data needed to prepare them. In the study of the structural problems of a belt of folded rocks in Wyoming and the preparation of structure contour maps of the area, the writer found it desirable to develop formulæ for calculating the thick-

[2] Green, A. H., "Geology, Part 1, Physical Geology," 1882, pp. 460, 464–467.
[3] Lahee, F. H., "Field Geology," New York, 1916, pp. 153–178, 405–417, 475.
[4] Hayes, C. W., "Hand Book for Field Geologists," New York, 1909, pp. 31–32.

ness of a number of formations under many conditions of folding. The principle upon which the formulæ are based, is used in the second graphic method referred to above; that is, that the outcrops are parts of concentric arcs (parallel).

ELEMENTS IN THE MEASUREMENT OF FOLDED BEDS.

In order to insure uniform consideration of each problem that may arise, the thickness of a group of beds between two detached exposures or outcrops is defined as the perpendicular distance from the outcrop of the overlying bed to the downward projection of the underlying bed. Thus, in Fig. 43, the thickness of the beds between Bed B and Bed D is DJ.

The following elements enter into the calculation of the thickness of such a group of beds.

(*a*) The true dip of each of the exposures or their true inclination from the horizontal.

(*b*) The horizontal distance between the two exposures.

(*c*) The difference in elevations of the two exposures.

(*d*) The assumption that may be made concerning the manner by which the beds were deformed or folded from the horizontal position, for this assumption determines the method that should be used in projecting the underlying bed downward.

(*a*) *The True Dip of the Beds.*—In the determination of the true dip of any bed it is first necessary that it be clearly observable, and this, as all geologists know, is not always the case. Many stratified rocks show minor laminations that diverge considerably from the surface of stratification and even these are locally so rough that their trend cannot be determined accurately. In many places, it is impossible to obtain good natural exposures but it is interesting to record that many companies exploring for oil now find it profitable to undertake considerable exploration to lay bare good surfaces of stratification, from which to interpret the local structures.

In considering thick masses of some varieties of sedimentary rocks, the question may arise whether the lower stratum actually persists to a point under the higher stratum with the same char-

acter shown at the outcrop. In the study of some coal and oil fields, careful study has shown that a coal bed or a sand, previously considered to be a continuous stratum, is really a group of overlapping lenses, each slightly higher in the section than another nearby. Considerable knowledge of the existing principles of stratigraphy may be needed in determining the actual thickness of thick sections of folded rocks.

Many clinometers and clinometer compasses are in use for the determination of the dip of bedding planes. Like many of the other instruments used by geologists, they are highly useful for reconnaissance work, but have definite limitations inherent in their small size.

In the experience of the writer, measurements of dip with the Brunton compass of such beds as the sandstones that make up a large part of the Mesozoic and Tertiary formations of the Rocky Mountains, are dependable at best only to the nearest degree and commonly to the nearest even degree. If the exposures permit and the accuracy is desired, dips with a probable error of less than 1 degree can only be obtained by determining the position and elevation of three points, preferably not more than 500 feet apart. The dip and strike are then determined by the method well presented by Rowe.[5]

(*b, c*) *Measurements of Distance and Difference in Elevation.* —It has not been long since geologists either scaled from a map or paced most of the distances needed in the field, and determined differences in elevation by the use of aneroid or hand level. Although these methods obviously have wide usefulness, their limitations are recognized and the light plane table and modern telescopic alidade equipped with stadia wires and vertical arc are now widely used where a higher order of accuracy is desired.

Hayes states:[6]

> Every field geologist should be able to measure distances by pacing, with an average error not greater than 2 per cent. on level ground and not greater than 10 per cent. on the roughest ground and steep slopes.

[5] Rowe, J. W., "Application of Descriptive Geometry to Mining Problems," *Amer. Inst. Min. Eng. Trans.*, vol. 41, pp. 512–514, 1910.

[6] Hayes, C. W., *loc. cit.*, p. 22.

Lahee states:[7]

> Distances obtained by pacing may be correct to 3 per cent. or less. The error may be reduced to 1 per cent. if the paces are frequently standardized. Taping with ordinary precautions is much more accurate, being correct to at least 1 in 3,000.

Lahee discusses the errors in triangulation by compass, sight alidade and telescopic alidade, but does not discuss the accuracy of stadia measurements. An inquiry among a group of geologists and topographers of the U. S. Geological Survey, all of whom are skilled in the use of the telescopic alidade (Gale type) for stadia work, indicates that the limit of error for sights less than 1,000 feet long is commonly less than 1 per cent. and for sights less than 2,000 feet long, less than 2 per cent. Differences in elevation of points 1,000 to 2,000 feet distant from the observer determined with these instruments, are thought to have similar limits of error.

(*d*) *Assumptions Concerning Manner of Folding.*—When a thick series of essentially horizontal beds is deformed the strongest beds will tend to resist internal deformation, the limiting surfaces of the individual beds will tend to remain parallel and the deformation will be largely adjusted by slipping along the surfaces between the beds. A group of strong beds will tend to form "parallel folds"[8] (*A*, *B*, Fig. 42). The weakest beds on the other hand will tend to be adjusted to the stresses of deformation by yielding internally and the limiting surfaces of individual beds will tend to assume "similar form" (*C*, *D*, Fig. 42). Probably in the strictest or most ideal sense, the beds of a fold are rarely if ever parallel over more than very small parts of the fold. In Fig. 42, *A* and *C*, represent "ideal types" of "parallel" and "similar" folds respectively. *B* has been prepared to show the manner by which, under the conditions commonly met, a strong bed (*b*) between weaker beds (*a* and *c*) is deformed. *D* has been prepared to show the manner by which a weak bed (*b'*) between

[7] Lahee, F. H., *loc. cit.*, 491.

[8] Van Hise, C. R., "Principles of North American Pre-Cambrian Geology," U. S. Geol. Survey, 16th annual report, part 1, pp. 596–600, 1896.

stronger beds (a' and c') is deformed. It will be noted that in ideal "parallel" folds (A), the thickness of the individual beds is constant throughout, whereas in "similar" folds (C), the thickness of the beds is different from place to place. Sections measured on both sides of the anticline along the line xx (Fig. 42, B) will yield the same results. On the other hand, a measurement of the thickness of the bed b' along yy (Fig. 42, D) on the

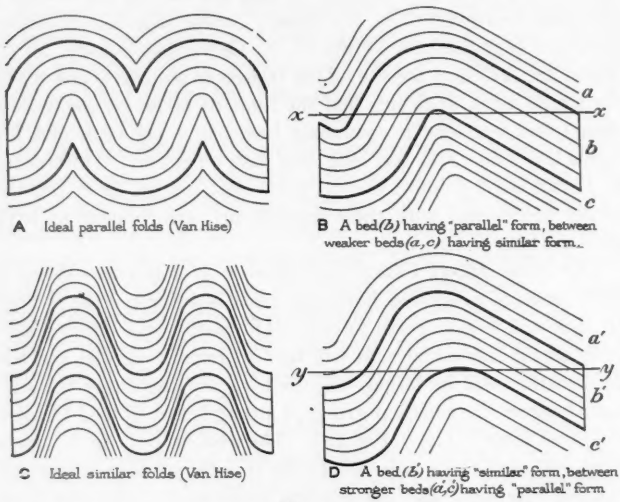


FIG. 42.

left side of the anticline will not agree with that measured on the right.

It is apparent, however, that in considering the problem of measuring the thickness of folded beds, there is primary concern only for those small parts of the fold that are exposed where erosion has beveled the limbs. Even though, in a broad way, the form of groups of beds is "similar," it is necessary to assume that the small parts available for measurement are "parallel." The proof that some beds of a thick folded section have under-

gone considerable internal flowage and that in a broad way, their form is "similar" can only be established when the thickness of several parts of the bed exposed by erosion each measured by assuming "parallel" form, differ appreciably. Obviously, the manner by which large thicknesses of strata are deformed is a large problem and will not be discussed further at this place.

CALCULATION OF THE THICKNESS OF FOLDED BEDS.

There are four possible cases in the determination of the thickness of folded beds, depending upon whether the folds are convex upward or downward and whether the surface rises or falls from the outcrop of higher dip to that of lower dip. The formula will be developed for one case only, but will be stated for the other three.

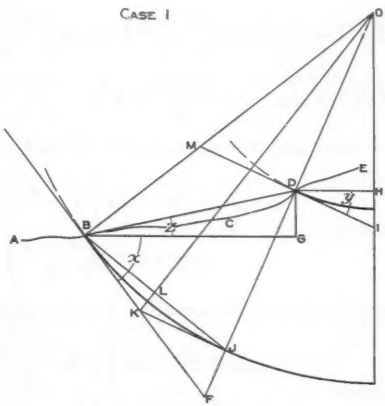


FIG. 43.

Case 1 (*Fig. 43*).—Beds are convex upward; the bed with greater dip is below the bed with lesser dip:

Assume that the two beds outcrop at B and D respectively along the surface $ABCDE$. The outcrop at B has a dip of $x = GBF$; the outcrop at D has a dip of $y = HDI$, and x is greater

than y. Draw BO so that $FBO = 90°$ and DO so that $IDO = 90°$. O is the common center of the two beds. The horizontal distance between B and D is BG and the difference in elevation is DG. Then $DBG = z$ and $\tan z = DG/BG$. It is desired to find the value of DJ = the thickness of beds between B and D, in terms of x, y, z, BG and DG.

Draw OK so that it bisects BOF, and intersects BJ at L, and BF at K. Now $DOH = y$, $BOI = x$, $BOD = x - y$, and

$$DOK = \frac{x-y}{2} \quad \text{and} \quad BJD = 90° - \frac{x-y}{2}.$$

In triangle BDJ:

$$DJ : BD = \sin DBJ : \sin BJD, \text{ or } \frac{DJ}{BD} = \frac{\sin DBJ}{\sin BJD},$$

but

$$\sin BJD = \sin\left(90 - \frac{x-y}{2}\right) = \cos\left(\frac{x-y}{2}\right)$$

$$\sin DBJ = \sin\left(x - \frac{x-y}{2} + z\right),$$

and $BG/BD = \cos z$ and $BD = BG/\cos z$. Hence,

$$DJ = \text{thickness} = \frac{\text{distance } BG \cdot \sin\left(x - \frac{x-y}{2} + z\right)}{\cos z \cdot \cos\left(\frac{x-y}{2}\right)}.$$

Where B and D have same elevation $z = 0°$, and

$$\text{thickness} = \frac{\text{distance } BG \cdot \sin\left(x - \frac{x-y}{2}\right)}{\cos\left(\frac{x-y}{2}\right)}.$$

There are other ways of expressing the value of the thickness, but in the writer's opinion this is the most convenient form. Those who are interested in using the formula, will find that the use of logarithms saves considerable time. In fact, the writer has made many solutions by using logarithms, at an average of less than three minutes each.

Derivation of formula for Hayes method:

$$\text{Thickness} = \frac{BM + FD}{2}.$$

In triangle BMD, the angle $MDB = y + z$, and the angle $MBD = 90° - x - z$. Therefore, the angle

$$\begin{aligned} BMD &= 180° - \text{angle } MBD - \text{angle } MDB \\ &= 90° + x + z - y - z \\ &= 90° + x - y. \end{aligned}$$

Now

$$\frac{BM}{BD} = \frac{\sin (y + z)}{\sin (90 + x - y)} = \frac{\sin (y + z)}{\cos (x - y)}$$

and

$$BM = BD \frac{\sin (y + z)}{\cos (x - y)}.$$

Also in triangle BDF, the angle $BDF = 90° - y - z$ and the angle $DBF = x + z$.

Therefore the angle

$$\begin{aligned} BFD &= 180° - \text{angle } BDF - \text{ angle } DBF \\ &= 90° + y + z - x - z \\ &= 90° - (x - y). \end{aligned}$$

Now

$$\frac{FD}{BD} = \frac{\sin (x + z)}{\sin [90° - (x - y)]} = \frac{\sin (x + z)}{\cos (x - y)}$$

and

$$FD = \frac{BD \sin (x + z)}{\cos (x - y)}.$$

Now

$$\begin{aligned} \text{thickness} &= \frac{BM + FD}{2} = \frac{1}{2}\left(\frac{BD \sin (y + z)}{\cos (x - y)} + \frac{BD \sin (x + z)}{\cos (x - y)}\right) \\ &= \frac{BG [\sin (x + z) + \sin (y + z)]}{2 \cos z \cos (x - y)}. \end{aligned}$$

Case II (*Fig. 44*).—Beds convex upward; the bed with greater dip is above the bed with lesser dip:

Assume that the two beds outcrop at B and D respectively, along the surface $ABCDE$. The outcrop at B has a dip of $x = HBF$; the outcrop at D has a dip of $y = IDJ$; x is greater than y. The angle $z = BDG$ and is determined by the relation $\tan z = BG/DG$.

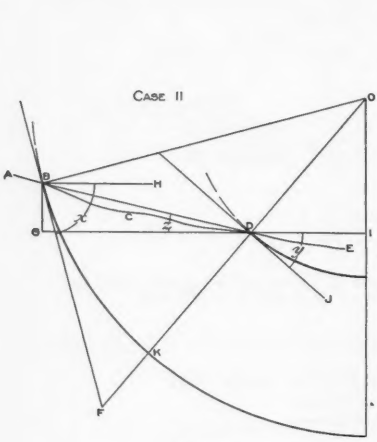


FIG. 44.

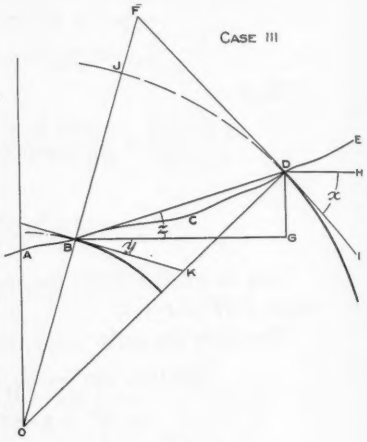


FIG. 45.

The solution will not be repeated.

$$\text{Thickness} = \frac{\text{distance } DG \cdot \sin\left(x - \frac{x-y}{2} - z\right)}{\cos z \cdot \cos\left(\frac{x-y}{2}\right)}.$$

Case III (*Fig. 45*).—Beds convex downward; the bed with greater dip is above the bed with lesser dip.

Assume that the two beds outcrop at B and D respectively, along the surface $ABCDE$. The outcrop at B has a dip of $y = GBK$; the outcrop at D has a dip of $x = HDI$; x is greater

than y. The angle $z = DBG$ and is determined by the relation $\tan z = DG/BG$.

$$\text{Thickness} = \frac{\text{distance } BG \cdot \sin\left(x - \frac{x-y}{2} + z\right)}{\cos z \cdot \cos\left(\frac{x-y}{2}\right)}.$$

Case IV (*Fig. 46*).—Beds convex downward; the bed with greater dip is below the bed with lesser dip.

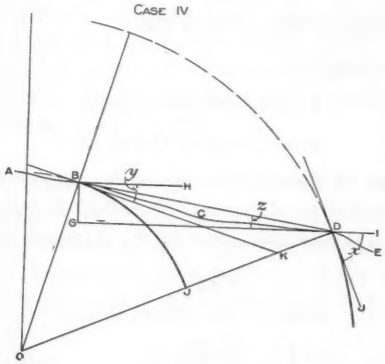


FIG. 46.

Assume that the two beds outcrop at B and D respectively, along the surface $ABCDE$. The outcrop at B has a dip of $y = HBK$; the outcrop at D has a dip of $x = IDJ$; x is greater than y. The angle $z = BDG$ and is determined by the relation $\tan z = BG/GD$.

$$\text{Thickness} = \frac{\text{distance } DG \cdot \sin\left(x - \frac{x-y}{2} - z\right)}{\cos z \cdot \cos\left(\frac{x-y}{2}\right)}.$$

In general, therefore, upon the assumption of parallel folding, the formula for the calculation of the thickness of folded beds

may be written as follows:

$$\text{Thickness } (T) = \frac{D \cdot \sin\left(x - \frac{x-y}{2} \pm z\right)}{\cos z \cdot \cos\left(\frac{x-y}{2}\right)},$$

where D = horizontal distance between two outcrops,

z = angle of slope between two outcrops,

x = angle of dip of steeper bed,

y = angle of dip of flatter bed.

In this formula, use

$(+z)$ in cases I and III,

$(-z)$ in cases II and IV.

Comparison of Results Determined by Hayes' Method with Those Determined by Assuming "Parallel" Folding.—In Table I. there are presented the values of the thickness (T) for pairs

TABLE I.

ERROR IN USING HAYES'S METHOD.

$$T \text{ (parallel)} = D\frac{\sin\left(x - \frac{x-y}{2}\right)}{\cos\left(\frac{x-y}{2}\right)}, \quad T \text{ (Hayes)} = \frac{D[\sin x + \sin y]}{2\cos(x-y)},$$

Dip of Steep Bed = x.	Formula.	Dip of Flatter Bed = y.									
		0°.		5°.		10°.		15°.		20°.	
		Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.
10°	Parallel..	87.5		130.7		173.6					
	Hayes...	88.1	0.7	130.9	0.2	173.6	0				
20°	Parallel..	176.3		218.3		259.8		301.0			
	Hayes...	182.0	3.2	222.1	1.8	261.6	0.5	301.6	0.2		
30°	Parallel..	268.0		308.0		347.3		386.0		424.2	
	Hayes...	282.1	5.3	323.9	5.1	358.4	3.2	392.8	1.7	427.5	0.8
40°	Parallel..	364.0		401.3		437.5		473.0		507.7	
	Hayes...	419.5	15.3	445.4	10.4	471.3	7.7	497.4	5.1	524.0	3.5

D = 1000 feet.

of dips, using first, the formula based upon "parallel" folding and second, Hayes's method. For the purpose of this comparison, it is assumed that the ground is level ($z=0°$). For each pair of dips, the column marked "per cent. excess" contains the per cent. excess of the Hayes figure over that obtained by using the "parallel" formula.

It will be noted that where the difference in dip is 10°, the Hayes figure exceeds the other by less than one per cent. Where the difference in dip is 20°, the excess ranges from 3.2 to 3.5 per cent. Only where the difference is 30°, does the excess become greater than 5 per cent. The table shows clearly that for the cases commonly met, where the difference in dip is less than 20°, the Hayes figure is a surprisingly close approximation to that obtained by assuming parallel form.

EFFECT OF ERRORS IN OBSERVATION OF DIP.

The following Table II. has been prepared to show the effects of small errors in observing dip. The table shows both the thicknesses of beds between pairs of outcrops 1,000 feet apart and the thickness that would exist if the steeper bed of each pair were increased 1°.

TABLE II.

$$T = D\,\frac{\sin\left(x - \frac{x-y}{2}\right)}{\cos\left(\frac{x-y}{2}\right)}, \quad D = 1{,}000 \text{ feet.}$$

Dip of Steep Bed $= x$.	Dip of Flatter Bed $= y$.									
	0°.		5°.		10°.		15°.		20°.	
	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.	Value T, Ft.	% Excess.
True 10°	87.5		130.7		173.6					
Observed 11° ...	96.3	10.1	139.4	6.7	182.5	5.1				
True 20°	176.3		218.3		259.8		301.0		342.0	
Observed 21° ...	185.3	5.1	227.2	4.1	268.5	3.3	309.4	2.7	349.4	2.1
True 30°	268.0		308.0		347.3		386.0		424.2	
Observed 31° ...	277.3	3.1	317.1	3.0	356.2	2.5	394.5	2.2	432.5	2.0
True 40°	364.0		401.3		437.5		473.0		507.7	
Observed 41° ...	373.9	2.7	410.8	2.3	446.8	2.1	481.8	1.9	516.2	1.7

It may be noted that the error caused by recording the dip 1 degree in excess of the true dip, makes a difference in the thickness that ranges from 7.4 to 9.9 feet for the pairs considered. The percentage error, however, ranges from about 10 per cent. for the pair $x = 10°$, $y = 0°$ to 1.6 per cent. for the pair $x = 40°$, $y = 20°$. As might have been expected, the percentage error is greatest for the low dips, and least for steep dips.

Now, it is interesting to consider the degree of error in measuring D, that corresponds to errors in measuring the dip.

1. Consider the pair $x = 10°$; $y = 5°$; $D = 1{,}000$ feet; then by the formula, $T = 130.7$ feet. Now change x to $11°$, leave $T = 130.7$; then $D = 937.5$ feet. In other words, an error of $1°$ in observing is equivalent to an error of 62.5 feet $= 6.25$ per cent. in measuring D.

2. Consider the pair $x = 20°$; $y = 10°$; $D = 1{,}000$ feet; then, $T = 259.8$ feet. Now, change x to $21°$; leave $T = 259.8$; then $D = 967.5$ feet. Hence an error of 1 degree in measuring dip is equivalent to an error of 32.5 feet $= 3.25$ per cent.

3. Consider the pair $x = 30°$; $y = 10°$; $D = 1{,}000$ feet; then $T = 347.3$ feet. Now, change x to $31°$, leave $T = 347.3$ feet, then $D = 975$ feet. In other words, an error of 1 degree in measuring dip is equivalent to an error of 25 feet $= 2.5$ per cent.

At least one conclusion may be drawn from the foregoing analysis. Reasonably careful work with the modern telescopic alidade with stadia wires permits horizontal measurements that are commonly within 2 per cent. and may be within 1 per cent. of the actual. Vertical control is commonly accurate within 1 per cent. If this order of accuracy is desired in measurements of the thickness of folded beds, it is necessary to use more care in the measurement of dips than the Brunton compass permits. To get this accuracy, outcrops should be very closely studied and the dip and strike of the beds determined by accurately locating the position and elevation of three points on each outcrop.

MEASUREMENT OF WIDTH OF OUTCROP.[9]

The same principle of "parallel" folding may be applied to determining the true width of outcrops in horizontal cross sections, where the line joining isolated outcrops is oblique to the direction of dip. The principle appears to be most readily applicable to belts of strong rocks.

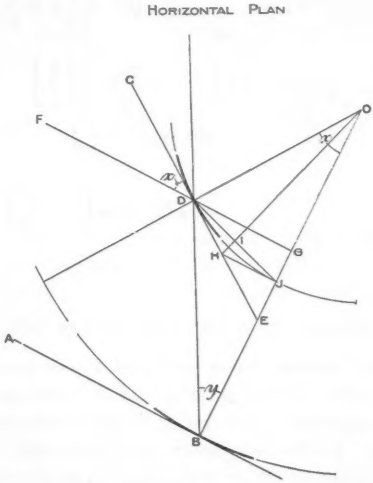


FIG. 47.

Assume that two outcrops at B and D, being parts of a parallel fold, have strikes of AB and CDE, respectively. (The direction of dip does not enter.) For simplicity, assume that AB is true north, so that the strike at D is FDC, east of north. Draw DO normal to CDE and BO normal to AB; O is the common center of the arcs. Draw OIH so that it bisects DOB; then draw DJ and DHE.

Now, $FDC = GDE = DOB =$ difference in strike $= x$. DB is the line connecting the outcrops, and $DBJ = 90° -$ the strike of $DB = y$. BJ is the true width of outcrop.

[9] Allen, A. H., *loc. cit.*, p. 467.

In triangle DBJ:

$$BJ:DB = \sin BDJ:\sin DJB \quad \text{or} \quad \frac{BJ}{DB} = \frac{\sin BDJ}{\sin DJB}.$$

But

$$DJB = 90° + \frac{x}{2} \quad \text{and} \quad BDJ = 180° - \left(90° + \frac{x}{2}\right) - y$$

$$= 90° - \left(y + \frac{x}{2}\right)$$

and

$$\frac{BJ}{DB} = \frac{\sin\left[90° - \left(y + \frac{x}{2}\right)\right]}{\sin\left(90° + \frac{x}{2}\right)}$$

and

$$BJ = \text{true width} = \frac{DB \cdot \cos\left(y + \frac{x}{2}\right)}{\cos\frac{x}{2}}.$$

MEASUREMENT OF INCLINED BEDS IN DETAIL.

It commonly happens that a geologist wishes to prepare a detailed stratigraphic section of a group of outcrops of inclined beds, whose aggregate thickness has been measured by plane-table methods. If the beds are nearly horizontal, this is ordinarily accomplished by using the Locke level, Brunton compass, or hand level in projecting the height from one's feet to one's eye as a unit of measurement.

Where the beds are inclined, Hayes[10] recommends the use of a 4 or 5 foot rod, to the end of which is attached a Brunton compass, with the clinometer level turned to equal the angle of dip. By looking through the compass the geologist observes the spot on the ground 4 or 5 feet stratigraphically higher than the point on which he is standing. He, thus, measures numerous units of 4 or 5 feet. As the geologist can rarely carry unnecessary equipment, the writer for a number of years has found the following method in regions of inclined rocks highly satisfactory. It is

[10] Hayes, C. W., *loc. cit.*, pp. 29–30.

essentially similar to the method recommended by Hayes, but depends upon the height to one's eye as a unit of measure. In

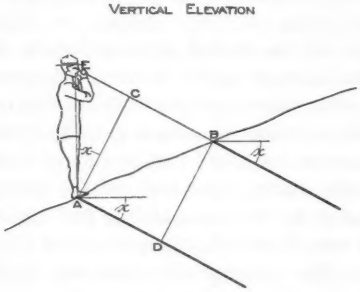


FIG. 48.

Fig. 48, the geologist stands at A, the base of the section to be measured. The clinometer level of the Brunton compass is turned to equal the angle of dip of the beds. When, therefore, the ob-

Dip = x.	$AE \times \cos x$.	Dip = x.	$AE \times \cos x$.
0	5.25	22	4.86
2	5.24	23	4.83
4	5.24	24	4.79
6	5.23	25	4.75
8	5.20	26	4.72
9	5.18	27	4.67
10	5.16	28	4.63
11	5.15	29	4.59
12	5.13	30	4.54
13	5.11	32	4.45
14	5.09	34	4.35
15	5.07	36	4.25
16	5.04	38	4.14
17	5.02	40	4.02
18	4.99	42	3.90
19	4.96	44	3.77
20	4.93	46	3.64
21	4.90	48	3.51

server looks through the sights, he observes a spot on the ground that is the distance $AC = BD$ stratigraphically higher than the point A at which he stands. Now $BD = AC = AE$ cosine of the

angle of dip $= AE \cos x$, and AE is constant for each observer. If, therefore, he prepares a table such as that given below, in which $AE = 5.25$ feet, he can readily determine the proper unit for each degree of dip.

The accuracy of the method depends largely on the facility with which the observer readily assumes the same posture, but also on the identification of the point which he is to occupy next. After many measurements of sections ranging from 500 to 2,000 feet thick, the writer has found that the sum of a number of such units is generally within 5 per cent. of the total thickness accurately measured by telescopic alidade and stadia, and rarely deviates 10 per cent. from such thicknesses, even in rough regions.

Conclusions.—The problem of measuring stratigraphic sections of inclined rocks resembles many others that a geologist encounters in that (1) the nature of the exposures determines the data that can be sought and recorded, (2) the time available largely determines the methods that should be used, and (3) the value of the results determines the order of accuracy that should be sought. It is highly important that he should know the order of accuracy that the available methods as well as the exposures permit.

The following general statements are presented for the benefit of those interested in constructing contour maps of prospective oil and gas fields in advance of considerable exploration, and of those interested in the deformation of beds as a result of folding.

1. In regions with considerable relief, sections of beds with less than 5° dip, or, in regions of low relief, beds that dip more than 80° can commonly be measured by telescopic alidade and stadia with a limit of error that does not exceed 2 per cent.

2. If, where a group of beds dip less than 20°, measurements that have errors of less than 5 per cent, are desired, horizontal distances and differences in elevation should be determined by the use of telescopic alidade and stadia and the strike and dip of the bedding surfaces should be determined by the use of the three point method described by Rowe.[11] In determining the thickness either the formula based on the Hayes method or those

[11] Rowe, J. W., *loc. cit.*, p. 512.

derived in this paper should be used. Graphic solutions are apt to introduce larger errors. If the Brunton compass is used to measure dips less than 10° it is unneccessary to use telescopic alidade and stadia to measure distances, for pacing and hand level have the same order of accuracy and the results will commonly have a probable error of 10 per cent. or more.

3. If, where stratigraphic units are bounded by beds that dip from 20° to 80° and the difference in dip is less than 10° a probable error of less than 5 per cent. is desired, measurements of distance and difference in elevation should be made by telescopic alidade and stadia; and measurements of dip by using the Brunton compass or similar clinometer. Thicknesses should be calculated by formulæ rather than graphic methods. If errors greater than 5 per cent. are permissible, graphic methods may be used.

4. If, as above, stratigraphic units are bounded by beds that dip from 20° to 80°, and the difference in dip is more than 10°, measurements should be made by telescopic alidade, stadia, and Brunton compass, and graphic methods based upon parallel folding will yield results with a probable error of 5 per cent. The formulas here set forth will probably save time, however, particularly if several calculations have to be made.

Other conclusions may be drawn from the data given by those especially interested in the subject.

The writer has used the formulas and methods set forth in this paper in the study of a highly folded region in Wyoming where several hundred sections ranging from 500 to 15,000 feet thick have been measured. Although it is recognized that the nature of the exposures, purpose of the work and time available for it will determine the order of accuracy obtainable in measuring stratigraphic sections, it is also firmly believed that the merits of precise methods justify their wider use. Certain problems in stratigraphy and in the structure of folded regions can only be advanced by close attention to accurate methods of measuring sections.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

CHALCOPYRITE DEPOSITS IN NORTHERN MANITOBA.

E. L. Bruce.

The deposits of chalcopyrite recently discovered and developed in Northern Manitoba lie near the western boundary of the province, a short distance northwest of Lake Athapapuskow, which is shown on Maps of Canada, fifty miles north of the Saskatchewan river. A large part of the journey from the railway at the town of The Pas, must be made by canoe in summer, or by sleigh in winter, and all the ore has been brought out during the winter months to the lakes that can be reached by steamers, and thence by scows down the Saskatchewan river.

TOPOGRAPHY.

The topography is rather monotonous for most of the distance from the railway to the producing area. Saskatchewan river flows in a number of changing channels through swampy country, and in many places is separated from broad, shallow lakes only by willow-covered levees. These lakes and the muskeg areas that border them act as reservoirs which are flooded during periods of high water. Northward from the Saskatchewan the same monotonously flat muskeg country continues to the boundary between the Pre-Cambrian and the Palæozoic formations. The rocks of the latter in many places stand up in an escarpment 70 to 80 feet above the lower lying but more rugged surface of the older rocks. In contrast to the unbroken level of the southern district with shallow, islandless lakes with low shores, the northern district abounds in ridges and hills, has only small muskeg areas and is dotted with almost countless, clear, island-studded, rock-bounded lakes of all sizes.

GENERAL GEOLOGY.

Since the rocks associated with the ores are all of Pre-Cambrian age it will be necessary only to mention that Palæozoic dolomites cover the older rocks south of lake Athapapuskow, and that Glacial and post-Glacial deposits form a discontinuous cover of varying thickness over all of the consolidated rocks.

The Pre-Cambrian succession is as follows:

Granite
Granite-gneiss
Hybrid granitic rocks
Intrusive contact
Arkose and conglomerate
Unconformity
Slate
Unconformity?
Granite porphyry
Intrusive contact
Sedimentary and igneous gneisses
Volcanic rocks and derived schists

Volcanic Rocks.—The oldest rocks are comparable to the oldest rocks of Pre-Cambrian age found in other areas, but, as they are separated from similar formations by great stretches of granites and gneisses to the east and by the Palæozoic cover to the south, it is not and may never be certain that they are of the same age as the Keewatin rocks of Lake Superior. They consist almost entirely of volcanic rocks of various types. The most common variety is massive, green to grayish-green in color and weathers to brownish color. The ellipsoidal structure figured in so many descriptions of Pre-Cambrian lavas is very strikingly developed and there are, in addition, certain other typical volcanic forms. Autoclastic bands have been formed by the rolling of the semi-solidified lava and by shearing. Pyroclastic beds are common. They have been formed by the incorporation of bombs of all sizes, from those a foot in diameter down to the finest ash, in the still molten rock. The pyroclastics have, superficially, much the appearance of some of the altered conglom-

erates of the district. All types, but chiefly the massive lava without the ellipsoidal structure, have been changed, locally, into chlorite schist by pressure and shearing. Some of this alteration occurred before the first period of erosion since, in the conglomerates overlying the volcanics, there are pebbles of schist which have not been sufficiently deformed by movements affecting the conglomerate to account for their schistose character. Associated with the volcanics there was probably deposited a certain amount of normal sediments, now altered to schists indistinguishable from those of igneous origin.

Complex of Gneissic Rocks.—Outside of the district in which the sulphide ores have been found there are areas of hornblendic gneisses and garnetiferous schists and gneisses that represent in part a sedimentary series apparently overlying the volcanics but with no recognized unconformity. These gneisses are intruded by granite sills and are cut by innumerable pegmatite dikes. The sills and dikes are believed to be of different ages, some of them older, some younger, than the conglomerates and arkose that lie above the greenstone series.

Granite Porphyry.—There is some evidence to show that one small batholith of granite porphyry is older than at least part of the sediments. The rock has rather peculiar bluish phenocrysts of quartz and under the microscope shows unusual, irregular, graphic intergrowths of quartz and feldspar, similar to intergrowths that occur in granite pebbles from the conglomerate.

Slate.—A narrow belt of slate has been found bounded on both sides by greenstone schist. No unconformity has been noted between the two rocks but the slate is lithologically like that lying unconformably above the volcanics farther west.

Conglomerate and Arkose.—The first formation that is clearly unconformable above the volcanic complex in the area is a thick series of conglomerate, arkose, and greywacke, now lying in closely folded synclines or as infaulted blocks in the older rocks. The folding following the deposition of these sediments has been so intense that even pebbles of quartz, granite, and quartzite, have been twisted, bent and drag-folded. Some of the lower beds consist largely of debris from the greenstone complex and

these have been reconstituted into rocks so closely resembling the igneous original that it is hard to delimit the exact boundaries of the sedimentary synclines.

Bedding in the sediments is not plainly marked, but in many places there is a lenticular arrangement, with very sudden variations both in composition and texture. These sudden changes, as well as the mineral constituents of the rocks, show rather conclusively that this series was deposited as outwash fans by rapid streams and probably under arid conditions. The close folding and the faulting that the sediments have undergone make a measurement of the thickness impossible but it must have been thousands of feet.

Granite Gneiss and Granite.—The diastrophic period that followed this final Pre-Cambrian sedimentation was accompanied by intrusions of granite. These took place through a considerable length of time and the intrusives vary somewhat in character but are believed to be differentiates from a common magma rather than products of different periods of intrusion. The ore is thought to be genetically related to certain of these differentiated magmas. Texturally, the granitic rocks are massive granite, in places porphyritic, and granite gneisses, faintly banded owing to a concentration of the basic constituents biotite and hornblende. There is no evidence of any great secondary rearrangement as the longer axes of the biotite foils are not parallel to the banding. In composition the gneisses are practically identical with the massive granite.

Analyses[1].	Granite Gneiss.	Granite.
SiO_2	67.71	66.76
Al_2O_3	14.69	15.39
Fe_2O_3	2.07	1.27
FeO	3.73	1.49
MgO	1.00	1.50
CaO	4.04	2.56
Na_2O	3.30	4.47
K_2O	1.28	3.35
H_2O	0.25	0.60
TiO_2	0.30	0.15
CO_2	...	undet
	99.37	97.54

[1] Analyst: M. F. Connor.

There is no evidence that there was further deposition or intrusion nor any very marked disturbances from the time of the invasion of the granite, throughout the rest of the Pre-Cambrian, the Cambrian, and part of the Ordovician. It was probably a period of normal erosion and must have been very long. The great thickness of cover under which the granite batholiths lay was almost completely removed and the mountains of that early period were levelled to a surface much like that at present found in the Pre-Cambrian area. This erosion reached to so great a depth that only the bottoms of the old synclines are left and in many places where the rocks are not actually granite they are a hybrid dioritic rock formed apparently by the incorporation of basic rocks by the slowly advancing border of the intrusive. The deposition of dolomite during part of the Palæozoic does not directly affect the consideration of the ores and will not be discussed here.

The glacial period was important in that the ice swept away much of the disintergrated material lying upon the rock surface, but it is not likely that it removed any great thickness of unaltered The deposition of lake and stream silts and the growth of muskegs in the undrained hollows have made it rather difficult to prospect much of the area, since the easily altered and eroded sulphides would naturally be removed to form the hollows in the rock floor, now filled with drift.

Geologic History.—The geologic history so far as it has been deciphered from the rocks of this district may be summarized as follows:

1. Outpouring of lavas and deposition of volcanic fragmental rocks with possibly some normal sediments.
2. Deposition without any break, of more acidic sediments now recrystallized into gneisses and schists.
3. Intrusion of granitic rocks.
4. A long period of erosion.
5. Deposition of two series of sediments, the later of which is largely terrestrial.
6. Mountain-making with a fairly long period of granitic intrusions during which the ores were brought in.

7. Extremely long period of erosion reducing the mountains to a mammillated surface of low relief.
8. Deposition of dolomite during the Palæozoic and possibly of shales during the Mesozoic.
9. Erosion of these to expose the Pre-Cambrian basement.
10. Glacial period.
11. Deposition of recent silts and formation of peat deposits.

THE ORE DEPOSITS.

Two important deposits of sulphide ores have been located, from one of which some ore has already been produced. The Mandy ore body is on a small point on the west shore of the northwest arm of Schist lake which drains into the north arm of lake Athapapuskow. The Flinflon deposit is on Flinflon lake, 4 miles northwest of the Mandy mine.

Both are in the volcanic series but there are marked differences in the character of the country rock and in the structure and mineralogy of the ore-bodies.

The Flinflon Lens.

The country rock to the east of Flinflon lake is massive greenstone displaying prominent ellipsoidal structure. To the west of the lake the greenstone is massive, dark green, and without this structure. Along a part of the deposit a narrow granite porphyry dike forms the hanging-wall; west of the ore zone there is a lamprophyre dike 25 feet in width. The sulphides occur replacing great shear zones in the greenstone. They form a series of overlapping lenses that unite and divide in a rather intricate fashion but, as only a small part of the zone is exposed, even the surface plan of the body is not known. Where it is exposed it has in one place a width of 75 feet but immediately south of this point, it divides around a horse of sparingly mineralized schistose rock. Diamond drilling on sections spaced at 500 feet, has proved that the sulphides extend for a length of about 2,500 feet and probably farther. The mineralized zone dips 60 to 70 de-

grees northeast and the drills are said to have proved its existence at a considerable depth.

The mineralization consists of almost solid sulphides bordered by disseminations in the wall rock. In the massive ore the only gangue materials are small blebs of quartz and some incompletely replaced country rock. Pyrite is the most abundant mineral but along certain zones there are bands of a fine-grained, purplish zinc blende and some chalcopyrite. Gold and silver are present but only in small quantities.

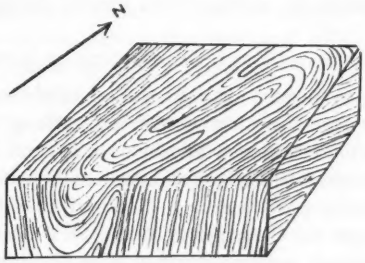
The Mandy Ore Body.

The country rock of the point upon which the Mandy is situated is dark green in color, with alternate bands of massive and of schistose rock. The ore body lies in one of the schistose zones. The ground plan of the body is elliptical, 225 feet in length by 40 feet in greatest width. It dips 75 to 80 degrees east. Leading out from the northwest and southeast sides of the lens, there are veins of sulphides striking parallel to the longer axis of the lens and to the schistosity of the enclosing rock. At the north end the ore pinches to a point and pitches beneath barren rock. At this point it is involved in a vertical fault zone that is approximately parallel to the strike of the lens but which does not show in the ore and possibly forms the hanging-wall of the ore body.

Glaciation has removed almost all the weathered products from the surface, practically fresh sulphides being exposed by removing the moss. The rocks are slightly stained by copper carbonates and it was this that first drew attention to the deposit. In small fissures in the sulphides, where water is not too abundant, crusts of chalcanthite have formed from the alteration of the copper minerals.

Formation of the Lens.—The deposit lies in the southwest limb of a syncline, the axis of which is occupied by conglomerate and arkose. The folding of the sediments, consisting of beds of unequal competence, crumpled the weaker beds into numerous drag folds which due to the plunge of the syncline northwestward appear on the surface as shown in Fig. 49. During the intense de-

formation that these rocks have undergone, the softer beds have suffered thickening at the crests and troughs of the minor folds



Drag fold on west limb of northerly pitching sincline

FIG. 49.

and thinning along the limbs. There has also been considerable shearing, the greatest amount of fracturing being localized at the troughs and crests of the folds. The surface plan of the ore

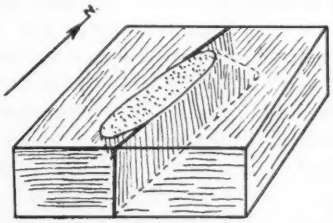


Diagram of supposed underground structure of Mandy sulphide body

FIG. 50.

body, its supposed form underground (Fig. 50), and its position with reference to the major structure of the country have led to the suggested hypothesis that the sulphide body is a min-

eralized drag fold, conditioned by the alternations of massive greenstone and chlorite schist which, squeezed between the more competent greenstone, crumpled and sheared during the folding.

MINERALIZATION AND PARAGENESIS OF MINERALS.

In the Mandy deposit the varieties of sulphides are individualized in larger bodies than at Flinflon. Along both foot and hanging-wall the sulphide is almost pure pyrite; the middle of the lens is occupied by chalcopyrite and zinc blende, the former being in a fairly pure band on the footwall side. The zinc blende envelopes the chalcopyrite filling the whole north end of the lens, and there are also interbandings of the two minerals. At the surface the chalcopyrite lens is 10 to 12 feet in width and 100 feet in length; at the 100-foot level it has widened to over 18 feet. Its strike does not parallel that of the main lens but cuts across it slightly. Gold and silver are both present in the ore but only in small amounts. The apparently homogeneous chalcopyrite is somewhat lighter in color than pure chalcopyrite should be and an analysis gives only 28.96 per cent. of copper. Polished specimens show inclusions of material that is black by reflected light and probably is country rock taken up by the ores. These inclusions are impregnated by pyrite and the edges of some of them are granulated and recemented by chalcopyrite and zinc blende. The pyrite is clearly earlier than the chalcopyrite since the latter includes fractured and granulated masses of pyrite. Some particles of the pyrite have a square outline, due perhaps to the control of the direction of fractures by the cleavage directions of the pyrite or to the original cubical form of pyrite crystals disseminated in the replaced rock (Plate XI., *A*). Specimens also show sphalerite in intimate relationship with chalcopyrite and evidently deposited at the same time as the copper mineral (Plate XI., *B*). Where chalcopyrite and sphalerite are interbanded there is no evidence of any fracturing of one with introduction of the other, or of any replacement, but in all cases the chalcopyrite bands contain sphalerite, and the sphalerite bands contain chalcopyrite. Fractured and partially replaced pyrite is nearly always present.

It seems that there was an early introduction of pyrite which replaced and impregnated the crushed and sheared rock of the drag folded zone of schist. Later movements fractured and granulated the pyrite, and chalcopyrite and sphalerite were introduced simultaneously. The segregation of these minerals into more or less individual zones may have been by selective precipitation due to the character of unreplaced country rock. There are still in the ore fragments of schist even after two periods of sulphide mineralization, and, naturally, there must have been even more unreplaced material before the deposition of the chalcopyrite and zinc blende. Since the country rock was schistose even at the time of the first mineralization, its replacement by pyrite would take place most easily along the planes of schistosity and, where the removal of the rock was not complete, the original schistose structure would be preserved by a banded arrangement of pyrite, partially replaced, and possibly almost unaltered rock. When the later sulphide minerals came in, these zones might so influence the precipitation that the banding would still be retained but with laminations of chalcopyrite and zinc blende taking the place of the pyrite and country rock of the first sulphide body.

ROCK ALTERATION.

The rocks in the vicinty of the sulphide deposits were originally dioritic in composition but have undergone great alteration, much of which was probably prior to the period of ore deposition. A massive ellipsoidal-weathering lava from Phantom lake, 2 miles west of the Mandy ore body, under the microscope shows a porphyritic texture with a few small scattered or nested crystals of plagioclase in a fine-grained groundmass. The crystals still retain the albite banding sufficiently to show that they are near oligoclase in composition. The groundmass consists of small crystals of much altered feldspar together with the products of the complete alteration of the original basic minerals now changed to epidote, chlorite, and calcite. The country rock on the east side of Flinflon lake is still more completely altered although it retains its ellipsoidal structure. Under the microscope

a thin section shows remnants of feldspar individuals but the alteration has gone too far to admit of the determination of their composition. The secondary minerals are chlorite, calcite, and sericite with considerable secondary quartz. This specimen was taken not far from the Flinflon sulphide body and it may have been affected to some extent during the period of mineralization.

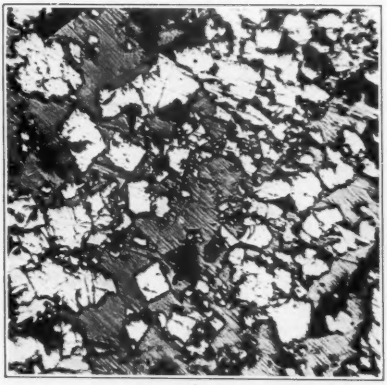
A specimen from the hanging-wall of the Mandy ore lens is a fine-grained, grayish, banded rock that effervesces freely with acid. Under the microscope it is seen to consist largely of secondary quartz traversed by a network of calcite. Calcite bands along the planes of foliation are somewhat larger than the connecting veinlets and give the rock a banded appearance. The footwall rock is more coarsely crystalline and has a large amount of pyrite scattered through it. In sections of ore, chlorite is the mineral most commonly included in the sulphides. The most striking difference between the rocks close to the ores and those that have not been affected by the ore deposition is the complete or almost complete removal of feldspars in the vicinity of the ores, with an increase in the amount of secondary quartz and some increase in the proportion of calcite. The alteration that the original lavas have undergone to change them to the greenstone into which sulphides were introduced, and the additional alteration that the mineralization has produced, are essentially similar, with, however, some silicification during the ore period.

NATURE OF ORE SOLUTIONS.

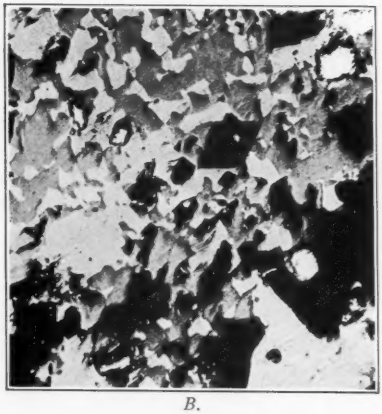
To produce such an alteration it seems necessary that the sulphides should have been accompanied by hydrothermal solutions. Many of the secondary minerals are hydrated and the presence of quartz and calcite in greater quantities than are found in rocks not affected by the mineralization is most easily explained by the action of aqueous solutions at fairly high temperatures.

GENESIS OF ORE.

The late granites are the most likely source of the ore solutions. An indication of this genetic relation is given by the oc-



A.



B.

A. Polished surface of ore from the Mandy sulphide body. White, pyrite (note cubes); gray, zinc blende; black, rock inclusions. × 185.

B. Polished surface of ore from the Mandy deposit. White, chalcopyrite; gray, zinc blende; black, included rock. This specimen shows the graphic intergrowth of the sphalerite and chalcopyrite. × 185.

currence of sulphide lenses, although not always cupriferous, along the margins of small bosses and dikes. The silicification of the wall rocks indicates that the solutions, at some stage of the mineralization, carried quantities of SiO_2, and solutions from a cooling granite mass would be expected to be siliceous in character. The copper zinc ores are referred to the late granite because they have not been crushed or altered by the movements accompanying the late intrusions. Bodies of granite are exposed at the surface at short distances from the ores and it is possible that the distance to the igneous rock may be even less underground than on the surface.

SUMMARY.

1. The rocks associated with the chalcopyrite deposits of northern Manitoba are much altered volcanics overlain by remnants of sedimentary rocks, and intruded by granite of at least two periods. These are all Pre-Cambrian.

2. The ore being mined comes from a segregation of chalcopyrite in a lens, made up of chalcopyrite, zinc blende and pyrite.

3. Bodies of pyrite were formed in shear zones in the greenstone or as replacements of drag folds in schistose bands.

4. Later fracturing was followed by introduction of chalcopyrite and zinc blende.

5. The sulphides are believed to be genetically related to the late granite intrusions.

GEOLOGICAL SURVEY OF CANADA,
OTTAWA, CANADA.

EXPERIMENTAL STUDIES OF SUBSURFACE RELATIONSHIPS IN OIL AND GAS FIELDS.[1]

R. VAN A. MILLS.

CONTENTS.

Introduction 398
Apparatus 399
Experiments 402
  Photographic Records 402
  Materials used 403
  Notes and Conclusions 404
  Methods and Technique 414
Application of Experiments 417
Summary 418
Need for Further Experimentation 420
Acknowledgments 421

INTRODUCTION.

During the writer's studies of subsurface problems in various oil and gas fields of the United States he has been impressed with the need for broad, systematic, and painstaking studies of subsurface relationships. New criteria for the interpretation of subsurface conditions must be established and new methods of work developed and applied in the search for oil and gas as well as in their recovery. The protection of our known fields against the inroads of water, and the development of more efficient methods of recovery are imperative, but both lines of endeavor depend primarily upon an understanding of subsurface principles and relationships. The drilling and operation of wells furnish valuable subsurface data, together with much costly experience, but the facts and relationships revealed through studies of materials and data collected in the field are not adequate because they are incomplete.

[1] Published by permission of the Director of the Bureau of Mines.

The United States Bureau of Mines is endeavoring to meet this situation through systematic and scientific field and laboratory experimentation. While investigating various phases of the oil-field water problem for the Bureau of Mines the writer has pursued experimental studies in conjunction with his field work. This has led to the development of a simple apparatus for the laboratory study of subsurface relationships in oil and gas fields. A series of preliminary experiments, with the apparatus demonstrated its value in studying some of the fundamental principles and relationships governing the occurrence and recovery of oil and gas. As there is a growing demand for this type of work, the apparatus, together with the methods of study that have been developed and some of the results of the work, will be of interest to other investigators.

APPARATUS.

Construction.—The apparatus consists essentially of a rectangular steel tank with removable top and front plates, and with openings and cocks arranged as shown in Fig. 51 and the accompanying plates. Three of these tanks, two small and one large,

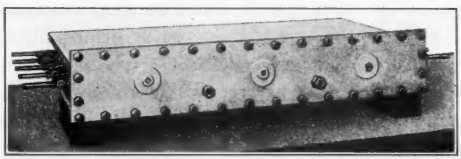


FIG. 51. Small experimental tank lying face down with cover plate attached.

are now in use by the Bureau of Mines. All pipe connections for the small tanks have ⅜ inch (0.95 cm.) internal diameters, and those for the large tank ½ inch (1.27 cm.) internal diameters. Standard brass service cocks are used on both sizes of tanks. All interior corners are slightly rounded through the bending of the steel members during construction, or through filling in corners with aquarium cement. The internal dimen-

sions of the two small tanks are 92 by 48 by 9 cm., or 36.22 by 18.90 by 3.54 inches; and of the large tank, 183.5 by 124 by 13.3 cm., of 72.24 by 48.82 by 5.24 inches. The fluid capacities of the two sizes of tanks are 39.7 liters (10.49 U. S. gallons) and 302.6 liters (79.94 U. S. gallons), respectively.

The steel bodies of the two sizes of tanks are built up of 5/16-inch plates riveted and welded to 4-inch and 6-inch channels respectively, the channels being bent so as to form the bottoms and ends of the tanks when standing vertically as shown in Plates XII.–XV. The surfaces of the steel members exposed on the insides of the tanks are enameled to prevent corrosion and to provide surfaces that approximate glass and quartz in their coefficients of friction with oil and water.[2] The legs of the channels, to which the plates are riveted, project outward as shown in the photographs. The backs of the small tanks are single plates, but the back plate of the large tank is equipped with two armholes and two removable plates to close them. Around the tops of the tanks there are planed flanges 5/16 inches thick, to which the top or cover plates may be bolted. The cover plates, which are 5/16 inches thick, fit snugly upon the flanges, the contacts being made tight by rubber gaskets. The cover plates are equipped with threaded openings and packing boxes which are closed unless in use. These openings serve principally to receive miniature wells. (See Fig. 51.)

The fronts of the tanks are removable glass plates that fit inside the steel frames and slide into place through the openings at the tops of the tanks when the cover plates are removed. The dimensions of the glass plates are ½ by 16 by 36 inches for the small size, and ¾ by 48 by 72 inches for the larger size. The tanks are constructed so that thicker plate glass may be used if desired. These plates are made tight to the steel frames by aquarium cement, and are braced from the outside by buckstays when necessary.

Uses.—This type of apparatus can be readily transported to field laboratories where it is desired to make repeated use of large

[2] Experiments with different enamels are in progress.

volumes of the gases, oils, and waters there found. When a tank is in use, such materials as sand, clay, gas, oil and water can be placed in the tanks and arranged to similate varied natural conditions. Loose sands can be compacted both by sedimentation and by tamping, and can be lithified through the use of different chemical reagents that react so as to cause cementation thus approximating the rock formations in nature.[3] Fluids can be introduced and made to pass through at will. Jet-like currents can be induced or prevented through regulating the velocities of flow and through the use of baffles which break up such currents. Pipes representing wells can be inserted and the fluids extracted through them. Moderate pressures can also be exerted, but for high-pressure work an auxiliary apparatus, to be described later, is being developed. While in use, the apparatus can be tilted to any desired angle. The total surface of glass in contact with the fluids is practically negligible in comparison with the total sand-fluid contacts. In other words, the conditions of experimentation can be made to approach more nearly to deep-seated rock conditions than can the conditions of experimentation in glass tubes or in open vessels. The plate glass fronts of the tanks afford every facility for making observations and photographic records, and the dimensions of the areas of glass exposed in the frames, together with graduations on the edges of the frames around the glass, afford size scales for the pictures. Furthermore, if the glass plates become badly scratched or broken, they can be easily replaced without injury to the apparatus. These features, together with the wide range of experiments that can be performed in the apparatus, are decidedly advantageous.

Three reservoir tanks for gases, oils, and solutions, together with an air pressure line connecting the reservoir tanks to an air receiver, form a part of the equipment. Pipe connections, gas meters, water meters, pressure regulators, thermometers, and gages, were arranged differently for the various experiments.

In using an apparatus of this kind it is imperative that the

[3] This process involves the formation of interstitial silicates and carbonates. It is used for the manufacture of artificial sand stone.

limitations of the experimental values be recognized. The difficulties of reproducing subsurface conditions in the laboratory necessitate the development of experimental methods to establish broad principles and relationships rather than concrete facts. In this connection, it is recognized that laboratory data have indicative and relative rather than absolute values as criteria for the interpretation of subsurface conditions and relationships; but in conjunction with field studies, the laboratory experiments broaden our conception and strengthen the foundation of facts upon which valid conclusions must be based. Field investigations, together with the laboratory study of materials collected in the field,[4] are therefore supplemented by experimentation in which comparisons are made between the behavior of different gases, oils, and aqueous solutions in different kinds of sands under different sets of conditions. The number of variables in each experiment is restricted so that the relative values of the factors and relationships under scrutiny, may, under the conditions of experimentation, be very definitely determined. In this respect, laboratory experimentation has a decided advantage over subsurface experiments in the field. Both types of work should be pursued; one or the other taking precedence according to the requirements of the problem. The reduction of the number of variables and the substitution of known for unknown values in formulating conclusions from both field and laboratory studies are just as important as the corresponding steps in solving an equation or a set of equations.

EXPERIMENTS.

Photographic Records.—To illustrate the use of the apparatus, photographs and brief descriptions of a few of the Bureau of Mines experiments in the laboratory are submitted for consideration. More complete descriptions of these experiments, together with notes showing the quantitative results, will be pre-

[4] See U. S. Geol. Survey Bull. 693. The evaporation and concentration of waters associated with petroleum and natural gas, by R. Van A. Mills and Roger C. Wells.

sented in later papers and in Bureau of Mines publications that are in course of preparation.

Materials Used.—The oils and sands that were used in these particular experiments are recorded in Tables I. and II., the oils

TABLE I.

OILS USED FOR EXPERIMENTATION.

Number.	Source of Oil.	Color.	Specific Gravity		Baume Gravity at 60° F. (15.6° C.).	Viscosity Expressed According to Engler.
			at 70° F. (21.1° C.).	at 60° F. (15.6° C.).		
1	Woodsfield, Ohio	Black	0.820	0.824	39.9	1.573
2	Tulsa, Oklahoma	"	0.861	0.865	32.0	2.073
3	Summerland, California	"	0.912	0.916	22.9	75.488

TABLE II.

SANDS USED FOR EXPERIMENTATION.[5]

Marks by which the Sands are Designated in the Photographs.	Ranges in Diameters of Grains Expressed in Millimeters.[6]	Total Porosities Expressed as Percentages of the Volumes of the Sands.[7]
a	6.350 to 1.651	36.00
b	0.833 to 0.589	38.00
c	0.417 to 0.074	37.00
d	1.168 to 0.833	37.00
e	0.589 to 0.074	38.00
f	6.350 to 0.833	37.00
k	0.295 to 0.074	40.00

being designated by numbers and the sands by letters which appear with the illustrations as well as in the tables. Only one quality of water, a chloride brine having a specific gravity of 1.100 was used. Air was substituted for natural gas. The temperature of experimentation was 70° F. (21.1° C.). In the different parts of each comparative experiment, equal volumes of air, oil, and water were used, under the same pressures and through equal periods of time, unless otherwise stated. With the apparatus arranged as shown in the accompanying photographs, the pressures never exceeded five pounds per square inch. The

[5] These are white quartz beach sands with rounded and partly rounded grains, except *c*, which is a fine sandy material from drill sludge.

[6] Screen analyses of these sands will be presented in later papers.

[7] Averages from five tests upon each sand, expressed to the nearest per cent.

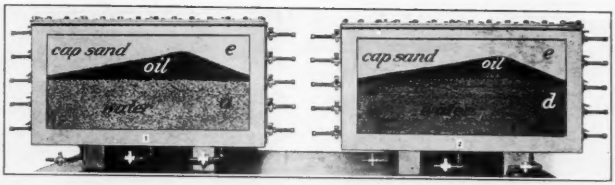
time periods varied from a few hours up to several months. In the recovery experiments illustrated by Plates XII.–XV., the miniature wells (⅜ inch pipes) extended 1 cm. (0.394″) below the tops of the pay sands and were 1 cm. inside the glass fronts.

Notes and Conclusions.—The following notes and conclusions from the experiments illustrated by the accompanying photographs are abbreviated to meet the purpose of this introductory paper as already outlined.

Experiment 1 (Plate XII., *a*) illustrates the "gravitational" segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in a coarsely porous sand (*a*, Table II.) and in a finely porous sand (*d*, Table II.). The oil was introduced at the bottoms of the tanks and allowed to migrate upward through the water-saturated sands under the propulsive force of its buoyancey in the water. The experiment had been in progress 48 hours when the photograph was made. The cap sand (*e*, Table II.) was a water-saturated beach sand, finer but more porous than either of the pay sands. This relatively fine water-saturated sand constituted a barrier to further vertical migration of the oil. Except for the textures of the two pay sands, the conditions of experimentation were practically the same in each tank. The reader will observe the more complete segregation of oil above water in the coarse sand *a*; and the sharp angles of repose[8] between oil and water in the finer sand *d*, as contrasted with the horizontal contact between the oil and water in the coarser pay sand *a*. In the finer sand *d*, the movements and adjustments of the fluids, especially the up-dip migrations of the oil, were slower and more restricted than in the coarser sand *a*.

Experiment 1 may be regarded as indicative of conditions in the crests of anticlines or in the upper parts of lenticular bodies of sand regardless of structure. Again, by tilting the apparatus, the experiment may be regarded as indicative of conditions in a single bed in which there are irregular textural variations. This

[8] In the descriptions of experiments the term "angle of repose" is used in a relative rather than an absolute sense.



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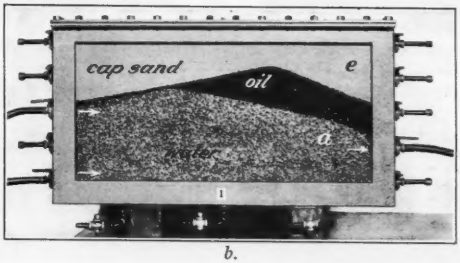

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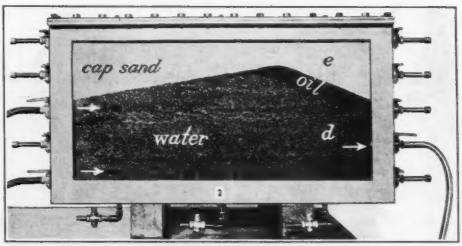
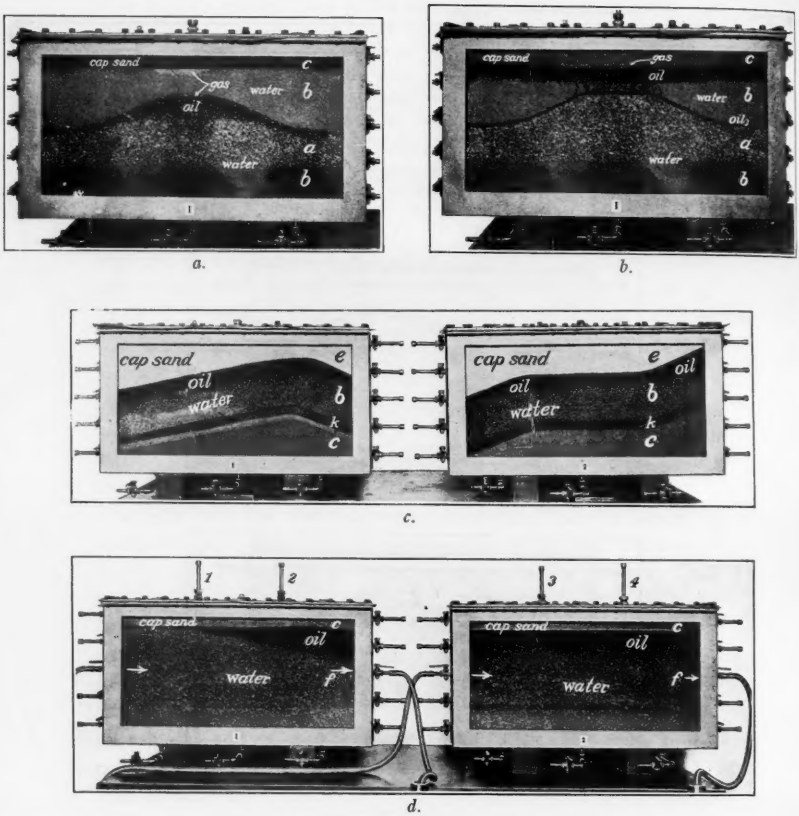


c.

a. The "gravitational segregation and accumulation of oil above water in sands of different textures. Tank 1 contained a relatively coarse pay sand (*a*), and tank 2 a relatively fine one (*d*). The cap sand (*e*) was water-saturated. Letters refer to materials in Table 2.

b and *c.* The "gravitational" and hydraulic segregation and accumulation of oil in sands of different textures. The arrows indicate the direction of flow.



a. *b*. *c*. *d*.

a and *b*. "Gravitational" segregation and accumulation of oil and gas above water in accordance with configuration of tops of sands. A-Oil and gas migrating upward into dome-like top of coarse sand *a*. B-Oil and gas migrating upward from coarse sand *a* into finer sand *b*.

c. "Gravitational" segregation and accumulation of oil in anticline and terrace. The dark beds *k* were fine oil-bearing sand (see table 2) which gradually gave up its oil to the overlying coarser sand *b*.

d. Differential movements between oils of different viscosities, and water, under same conditions of hydraulic flow. Tank 1 contained relatively non-viscous Appalachian oil (1); tank 2 more viscous Mid-Continent oil (2).

experiment, supplemented by many others of the same type, indicates that, other conditions being equal, the textures of oil and water bearing sands, more especially the sizes of pores in the sands, are primary factors governing the migration, accumulation, and mode of occurrence of oil. The angles of repose between oil and water in sands depend, among other things, upon the sizes of pores in the sands. The degree of dip is also a primary factor influencing both the angle of repose between oil and water and the up-dip migrations of the oil. Under ordinary hydrostatic conditions in water bearnig sands, oils of the Appalachian and Mid-Continent types (see oils 1 and 2, Table I.) migrate up dip until angles of repose between oil and water are established. These migrations are influenced and may be restricted or prevented by textural variations in the sands. Sharp reductions in the sizes of pores in water-bearing sands may, under favorable conditions, constitute textural barriers against which oil accumulates in the coarser pores. This is illustrated by the effects of the fine water-bearing cap sands *e* and *c* used in this and the other experiments herein described.

Experiment 2 (Plate XII., *b*, *c*) illustrates the "gravitational" and hydraulic segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in a coarsely porous sand (*a*, Table II.) and in a finely porous sand (*d*, Table II.). The cap sand (*c*, Table II.) was a water-saturated beach sand, finer but more porous than either of the pay sands. This relatively fine water-saturated sand constituted a barrier to further vertical migration of the oil from the coarser sands *a* and *d*. At the beginning of the experiment the fluids were as shown by Plate XII., *a*. The migrations and rearrangements of oil and water yielding the conditions shown in Plate XII., *b* and *c*, were induced by hydraulic currents in the directions indicated by the arrows. Under the same pressure (3 foot head of water) and during the same time (10 minutes) the volume of water (25 liters) displaced from the coarse sand *a* was five times that displaced from the finer sand *d*, though the finer sand was the more porous of the two. The reader will observe the smaller volume of accu-

mulated oil, as well as the steeper, though less sharply defined, oil-water contact in the finer pay sand *d*. A large proportion of the oil in tank 2 was lost through retention in the fine pay sand. Effects similar to these were induced in the laboratory by currents having only one tenth the velocities used in this experiment but extending through longer periods of time.

Experiment 2 may be regarded as indicative of conditions resulting from hydraulic currents in the crests of anticlines or in the upper parts of irregular or lenticular bodies of sand regardless of structure. Again by tilting the apparatus, the experiment may be regarded as indicative of similar conditions in a single bed in which there are irregular textural variations. The experiment indicates that under favorable conditions, the oils of the Appalachian and Mid-Continent types (see oils 1 and 2, Table I.) migrate up or down dip under the influence of slight hydraulic currents. These migrations are, of course, influenced, and may be prevented, by the textural conditions in the sands. The slopes of the sands and the rates of the hydraulic currents are factors of primary importance. This and many other experiments indicate that the loss of oil through retention in the sands incident to induced movements of oil and water, depend among other things upon the sizes and shapes of the pores in the sands. The greatest losses by retention occur in the sands having relatively fine angular pores.

Experiment 3 (Plate XIII., *a* and *b*) illustrates the "gravitational" segregation and accumulation of oil and gas above water in accordance with the configuration of the tops of the sands but not necessarily in accordance with structure. At the beginning of the experiment the sands were saturated with water(chloride brine, sp. gr. 1.100) except for entrapped air which slowly segregated and accumulated above the water. Oil (1, Table I.) was introduced in three equal volumes through the respective openings at the bottom of the apparatus while the water displaced by the oil escaped through the center opening in the top plate.

Plate XIII., *a*, shows oil and air migrating upward from the relatively fine water-saturated sand *b* into the dome-like top of

the coarser water-saturated sand *a*. The photograph was made thirty minutes after the oil was introduced. The upper bed of water-saturated sand *b* in contact with *a* constituted a temporary barrier to further vertical migration of the oil and air which migrated up the slope of the contact between *a* and *b*. Within 24 hours after this photograph was taken, the cumulative buoyancy of the oil and air accumulating in the dome-like top of *a* overcame the resistance to further upward migration. The oil and air broke through the contact along the crest of *a*, where the propulsive force of cumulative buoyancy was greatest.

Plate XIII., *b* shows the oil and air migrating "gravitationally" from the coarse sand *a* into the finer sand *b* and reaccumulating under the fine water-saturated cap sand *c*, 48 hours after the oil was introduced. The lateral migration of oil and air through the fine water-saturated sand *b* in the absence of any slope in the top of that sand is especially interesting. The relatively fine water-saturated sand *c* constituted an effective barrier to the further upward migration of the accumulating bodies of air and oil which flattened out to assume positions of repose above the water.

Experiment 3 indicates that under such conditions of retarded migration, the cumulative buoyancy of oil and gas in water-bearing sands is a primary factor in both the accumulation and the recovery of oil and gas. It further indicates that the so-called "up-dip" migrations of oil in regions of low dip and the deep-seated movements and rearrangements of oil and water incident to the drilling and operation of wells, more especially the elimination of water cones, are due in part to the flattening out of bodies of oil when they are assuming their angles of repose above water. The presence of gas in a water-bearing sand with the oil evidently facilitates the lateral as well as the vertical adjustments. The experiment further indicates that there is a tendency for oil and gas to migrate upward under hydrostatic conditions in water-saturated strata and to accumulate where further upward migration is prevented by structural or depositional doming, or by textural or other barriers, in ac-

cordance with the underlying principles of the anticlinal theory but not necessarily in accordance with structure.

Experiment 4 (Plate XIII., *c*) illustrates the "gravitational" segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in an anticline and in a terrace. The dark bands *k* under the pay sands *b* were fine oil-bearing sand which gradually gave up its oil to the overlying coarser sand. In these oil and water saturated sands, the vertical migration and adjustments of the oil toward static equilibrium occurred more readily than the horizontal adjustments, thus giving rise to the inclined, though irregular, oil-water contacts. There was a tendency for the oil to migrate up dip and for the oil-water contacts to flatten until angles of repose between the oil and water were established.

The experiment indicates that the up-dip migration and segregation of a light, non-viscous oil above water, under the propulsive force of buoyancy, plays an important rôle in the accumulation of such oils in both anticlines and terraces. The entrapment of oil in terraces also depends upon the resistance to the lateral migration of the oil across and beyond the terraces. This resistance to lateral migration depends largely upon the textural conditions, more especially upon textural barriers in the sands and also upon the shape and extent of the terraces. Under favorable conditions, oils of the Appalachian and Mid-Continent types (oils 1 and 2) migrate up dip under the propulsive forces of their buoyancy in water. Structure and conditions that are analogous to structure are of primary importance both in the accumulation and in the recovery of such oils. This is one of the experiments in a series indicating that the angles of repose between oil and water, under hydrostatic conditions, in sands depend upon the summations of the effects of many factors among which the slopes of the tops of the sands, and the textural conditions in the sands, more particularly the bedding and sizes of pores are of primary importance.

Experiment 5 (Plate XIII., *d*) illustrates differential movements between oils of different viscosities and water under the

same conditions of hydraulic flow. Oils 1 and 2 were introduced into water-saturated pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment the bodies of accumulated oil lay horizontally above the water. Under the influence of water currents passing through the pay sands, and involving the displacement of 15 liters of water from each tank during a time period of 30 minutes, both bodies of oil were moved in the direction of flow. The least viscous oil, in tank 1, underwent the most extensive movement and the most complete rearrangement. The water advanced most readily ahead of the more viscous oil in tank 2. Under practically the same conditions of experimentation, oil 3 was not moved by the hydraulic currents. It remained practcally stationary while the water advanced ahead of it.

The experiment indicates that the influence of natural or induced water currents upon the migration, accumulation, and recovery of oil depends primarily upon the physical properties of the oil, more especially its viscosity, together with the numerous other subsurface conditions and relationships. Other conditions being equal, the differential movements between relatively viscous oils and water are more pronounced and under certain conditions, are more detrimental to the recovery of the oil than are such movements and rearrangements between non-viscous oils and water.

Experiment 6 (Plate XIV., *a*) illustrates the formation of water cones through the differential movements of oil and water to wells. Oils 1 and 2 were used in pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment, the accumulated bodies of oil lay horizontally above the water. The propulsive force was exerted by the pressure of the advancing water. The rates of extraction from wells 2 and 4 were more rapid than from wells 1 and 3. In both tanks, water advanced to the wells ahead of the oil, thus forming the so-called water-cones. This was most pro-

nounced with the relatively viscous oil in Tank 2. Again, in both tanks, the advance of water ahead of the oil was most pronounced where the rates of extraction through wells were most rapid. Also the light non-viscous oil in Tank 1 moved most readily to the wells thus giving rise to greater interference between wells in tank 1 than in tank 2. The loss of the relatively viscous oil in tank 2 by retention in the pay sand was greater than with the non-viscous oil in tank 1. These relationships are illustrated by Plate XIV., *a*, the photograph having been made 30 minutes after continuous extraction through the wells commenced. As production from the wells continued, the proportions of water recovered with the oil increased. This was especially noticeable with the more viscous oil in tank 2. Under the conditions of experimentation there appeared to be direct relationship between the oil-water ratios and the rearrangements of the fluids in the sands.

This experiment, together with many others of the same type, upon water-cone phenomena, indicate that the formation and effects of water cones depend primarily upon the qualities as well as upon the modes and proportions of occurrence of the fluids; the qualities of the reservoir rocks, more especially the bedding, thickness, and sizes of pores; and upon the practice of drilling and operating wells, more particularly upon the manner and rates of extraction. Rapid and continued extraction tends to accentuate the formation of water cones.

Experiment 7 (Plate XIV., *b* and *c*) illustrates the formation of water cones through differential movements between oils and water when the propulsive force was exerted by expanding gas. Oils 1 and 2 were used in pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment, the accumulated bodies of oil with small proportions of absorbed gas (air) lay horizontally above the water. In the recovery of oil, gas, and water through the wells, the propulsive force was exerted by compressed air admitted at the bottoms of the tanks. The extraction was more

rapid through wells 2 and 4 than through wells 1 and 3. During periods of 30 minutes, 25 cubic feet of air under pressure of one pound per square inch were admitted into each tank; the oils and water thereby displaced being recovered from the wells as foams of oil and water with air.

Attention is called to the ebullition of gas (compressed air) through the oils, and to the greater tendency of the gas to cut across the top and ahead of the less viscous oil in tank 1. The propulsive work of the expanding gas upon the relatively viscous oil in tank 2 was the more efficient because the viscous oil became more readily entangled with the gas thus preventing its free passage and escape to the wells. This advantage of the viscous oil was offset by the greater force required to propel it through the sand.

This experiment, together with a series of experiments of the same type, emphasizes the need for underground conservation of the compressed gases accompanying oils, especially viscous oils, in their "pays." The experiments also indicate that to obtain the maximum increase in the recovery of viscous oils by the Smith-Dunn compressed air process,[9] comparatively high air pressures should be used to overcome the greater resistance to the movements of these oils. By maintaining high pressures, either natural or artificial, and by letting the wells flow intermittently, advantage may also be had from the oil coning and skimming phenomena illustrated by the next experiment (see Plate XV., *a*).

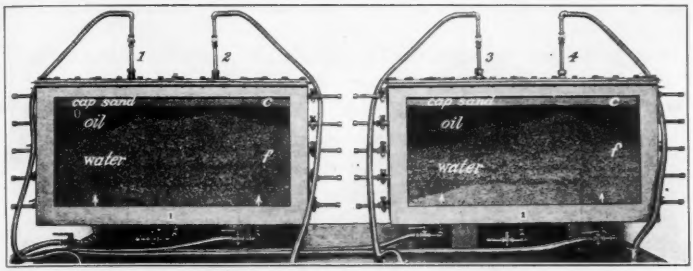
Experiment 8 (Plate XV., *a*) illustrates the formation of an oil cone through the differential movements of oil, gas, and water when the propulsive force was exerted by expanding gas. In this experiment there was a greater proportion of gas to oil and a smaller proportion of water to oil than in the preceding experiment (see Plate XIV., *b* and *c*). At the beginning of the experiment the accumulated body of oil (1, Table I.) lay horizontally above the water and below an accumulated body of gas. The compressed gas that exerted the propulsive force, and which

[9] See Lewis, J. O., "Methods for Increasing the Recovery from Oil Sands," U. S. Bureau of Mines Bull. 148, 1917.

was admitted at the ends rather than at the bottom of the apparatus, became absorbed and entangled with the oil which was propelled toward well No. 2 ahead of the water. In this experiment the oil was literally skimmed from above the water, the ratio of oil to water recovered being better than in any of the preceding experiments. During a period of 20 minutes, at the end of which the photograph (Plate XV., *a*) was taken, 122 cubic feet of compressed air under a pressure of one pound per square inch were admitted into the apparatus.

This and many other experiments of the same type indicate that under favorable conditions, oil under the propulsive force of expanding gas, advances to wells ahead of the associated water. As the gas is exhausted, these advantageous relationships change, and water may advance ahead of the oil. The mode of occurrence of the fluids, the proportions in which they occur, and the movements and rearrangements that they undergo incident to the drilling and operation of wells are of primary importance in recovery problems.

Experiment 9 (Plate XIV., *d*) illustrates the entrapment of oil and gas in irregularities at the top of a water-bearing or flooded pay sand (*b*, Table II.). At the beginning of the experiment the gravel at the base of the apparatus was saturated with water (chloride brine, sp. gr. 1.100) which was overlain by a horizontal body of oil (1, Table I.) in the coarse sand *a*. The sands overlying the gravel were moistened with water when they were packed into place. These sands were slowly flooded by admitting water through the openings at the bottom of the tank. A large part of the air displaced during this procedure was allowed to escape through the center opening in the cover plate. As the water-level rose, a part of the oil was floated upward, while a large proportion was also retained throughout the pay sand, the water advancing ahead of it. Part of this retarded oil continued to migrate upward, as in the other experiments. Upon reaching the water-wet cap sand *e*, the oil assumed an inclined position against that barrier. The further upward migration of the oil with its included air was diagonal rather than vertical. The



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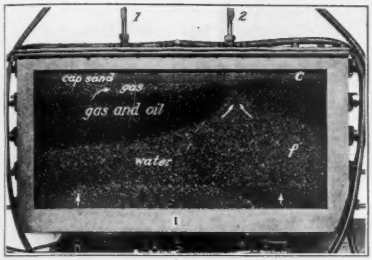

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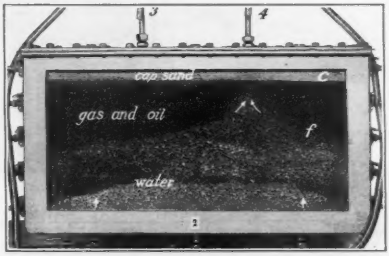

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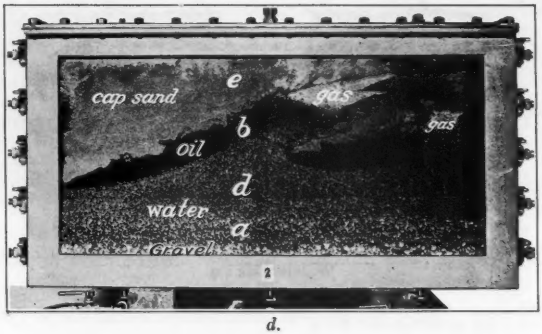
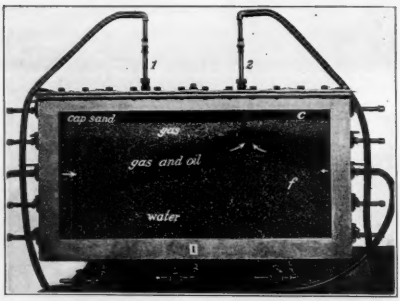


d.

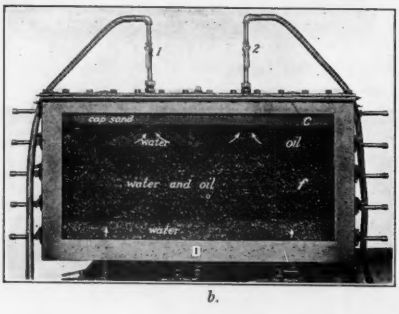
a. Water cones formed through the differential movements of oil and water to wells, when the propulsive force was exerted by advancing water. Tank 1 contained a relatively non-viscous Appalachian oil (1); tank 2 more viscous Mid-Continent oil (2).

b and *c.* Water cones formed through differential movements of oil and water to wells when the propulsive force was exerted by expanding gas. Tank 1 contained a relatively non-viscous Appalachian oil (1, table 1). Tank 2 contained a more viscous Mid-Continent oil (2, table 1).

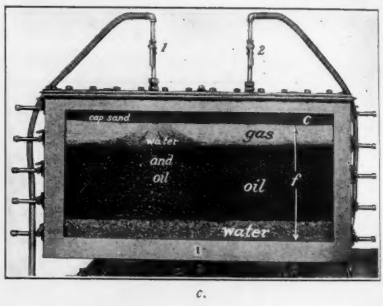
d. Entrapment of oil and gas in irregularities at top of water-bearing pay sand.



a.



b.



c.

a. Oil cone formed during recovery of oil and gas under propulsive force of the expanding gas.

b and *c.* Injury to an oil and gas well by infiltrating water; *b*, water leaking into pay sand through well No. 1; *c*, water being recovered through well No. 1 and oil through well No. 2.

photograph (Plate XIV., *d*) shows the oil and air migrating upward and accumulating in the entrapments above the water at the end of the 30 minute period of flooding.

The experiment was repeated by first saturating the sands with water and then introducing air and oil through the openings at the base of the apparatus. The water displaced during this procedure was allowed to escape through the center opening in the cover plate. Under the propulsive force of their buoyancy in the water, the gas and oil migrated upward into the entrapments, the movements being slower but of the same order as those just described. In both parts of the experiment the accumulating bodies of oil flattened out until they assumed angles of repose with the water. The oil in the uppermost entrapment was not displaced by hydraulic currents through the underlying sands but was readily displaced by air segregating and accumulating in the top of the entrapment.

This experiment indicates that the entrapment and retention of oil and gas along the irregular tops of water-bearing or flooded pay sands may be a common cause of underground loss of oil and gas. Much of the oil so entrapped should be recoverable by the Smith-Dunn compressed air process.[10] Numerous experiments of this type indicate that air segregating above the oil liberates the oil from such entrapments. The experiment also indicates that under favorable conditions the wells tapping such irregularities at the tops of water-bearing pay sands may be benefitted by induced migration, segregation, and accumulation.

Experiment 10 (Plate XV., *b* and *c*) illustrates the injury to an oil and gas well by infiltrating water. Water-bearing cap sand *c* and pay sand *f* were used. Plate XV., *b*, shows water leaking in through well No. 1 and flooding the pay sand *f*. Part of the water thus leaking into the pay sand was retained, by capillarity, in the pores of the sand around the well. Plate XV., *c*, illustrates an advanced stage in the recovery of oil from the flooded pay sand, the leak through well No. 1 having been stopped before production was commenced. Water with only a trace of

[10] Described by J. O. Lewis in U. S. Bur. of Mines Bull. 148.

oil (2) was recovered from well No. 1, whereas oil with very little water was recovered from well No. 2. Practically all of the oil recovered came from well No. 2 because the sand around well No. 1, while permeable to water, was relatively impermeable to oil. The propulsive force was exerted by the pressure (3 foot head) of water admitted through the bottom of the apparatus. A large proportion of the oil, originally present, was lost by retention in the pay sand as is shown in the photograph (Plate XV., *c*) by the black patches of oil throughout the otherwise white pay sand. The injury to well No. 1 was remedied in the laboratory by introducing enough of oils 1 or 2, and under sufficient pressure, to displace the water from the pay sand around the well; and then, by operating the well very slowly with long periods of rest to prevent water coning.

This experiment indicates that the selective or differential permeability of sands to water or oil is an important factor in the recovery of oil from sands. The selective or differential permeability of a sand to oil or water depends very largely upon the order and degree with which the sand has been wet or saturated with one fluid or the other. The infiltration of water into a pay sand may render the sand selectively permeable to water and relatively impermeable to oil at that place. This appears to be one of the primary causes of injury to oil wells and to productive sands by infiltrating waters. Other causes of injury to wells and to productive sands, such as the salting up of wells, the corrosion of casing, and the plugging of the pores of productive sands by organic and inorganic matter, through the agencies of water, together with modes of preventing and remedying these injuries, have been studied through other experiments that will be presented in later papers.

Methods and Technique.—The results of such experiments depend largely upon the methods employed, but to fully describe the methods and technique that have been developed by the Bureau of Mines would require more space than is here available. Only a few points upon methods and technique demand brief consideration at this time.

In attacking obscure subsurface problems, especially those of oil and gas migration, accumulation, and recovery, the investigator should proceed with an open mind without being unduly influenced by preconceived ideas which may hold true in one locality but not in another. Efforts to prove ideas before submitting them to adequate and unprejudiced field and laboratory study have too frequently led to conclusions that are worse than wrong because they are misleading.

The fact is emphasized that laboratory experiments on the movements of oil, gas, and water, through sands must be performed upon a scale sufficiently large to avoid the misinterpretation of capillary phenomena. The effects of capillary forces must be compared with the effects of other forces, but for this kind of work, the conditions of experimentation, more especially the size scale of the experiments, must be adequate. To restrict the work to the conditions and dimensions of movements by capillarity may lead to serious errors. In meeting these requirements, the writer works with saturated[11] as well as unsaturated sands in the two sizes of tanks that have been described.

Experimentation should be conducted systematically, directed toward elucidating first principles, and then working in accordance with them. In all of the Bureau of Mines experiments in the laboratory, the first step is to study the physical and chemical properties of the materials to be used, and to plan, approximately at least, the physical conditions of experimentation that are to be maintained. Unless the qualities of the various materials used in the experiments are studied, there can be no adequate basis for comparing different experiments or for drawing conclusions from single experiments. It is not sufficient to regard pay sands merely as sand, or to regard oils, gases, and waters merely as oil, gas, and water. The chemical and physical qualities of the reservoir rocks and fluids they contain have a wide range of variation; consequently their subsurface relationships are rarely, if ever, alike in different localities or at different

[11] These terms are used in a relative rather than an absolute sense, to indicate the degree with which the pores are filled with oil and water.

depths in the same locality. Experimentation must be conducted in the light of these facts.

In order to restrict the number of variables in the laboratory experiments, certain known conditions in the parts of experiments that are under comparison are maintained as nearly identical as possible. To satisfy this requirement, uniform methods of preparing, loading, and tamping sands and clays into the tanks and of introducing oils, gases, and aqueous solutions into these sands and clays, were devised and followed for each comparison. For the experiments illustrated in this paper, the sands were introduced in thin layers through the open tops of the tanks, and uniformly tamped as they were being loaded. Tamping must be done very carefully, as otherwise there may be a subsidence of the sand or clay during the experiment, which may give entirely misleading results. The use of compressable rubber gaskets under the cover plates is advantageous to take care of slight subsidences that may occur. The fluids are loaded together with the sands or are introduced through openings in the tanks after the sands and clays are in place. In some of the experiments, not here illustrated, perforated pipes extending through the sands are used to introduce the fluids. Fresh, clean sands are used in each experiment and strict cleanliness is observed. These sands are screened and washed alike and practically all extraneous material is removed to prevent the deposition of silt in the pores. These and the other precautions that have been outlined are necessary for making accurate comparisons.

Photographic records of the experiments furnish convincing evidence to accompany the notes and facilitate detailed studies and comparisons subsequent to experimentation. Phenomena that escape observation during the experiments are made apparent and can be studied through these records. Certain precautions are, however, necessary to make clear photographs. Smudges of oil, and finger marks upon the glass fronts of the tanks must be avoided or removed, and high-lights together with other reflections seen from the camera must be eliminated. It must be emphasized that careful, painstaking work, close ob-

servation, and adequate, systematic notes, in the laboratory as well as in the field, are imperative.

APPLICATION OF EXPERIMENTS.

Through the methods that have been outlined, the Bureau of Mines is now studying the induced effects[12] in oil and gas fields, or in other words, the deep-seated effects that are induced by man's activities. It has long been recognized that physical and chemical equilibrium in the reservoir rocks are disturbed by the drilling and operation of wells, but the importance of studying these effects to establish primary causes for underground losses of oil and gas is only beginning to be recognized. Such studies of causes and effects throw important light upon underground problems, and facilitate the development of better methods of recovery. The primary causes of injury to wells and to the productive sands themselves through the agency of water are being established and methods of preventing and remedying these injuries are being developed. The modes of occurrence of oils, gases, and waters in their reservoir rocks and the factors governing these modes of occurrence are being studied. Special attention is being given to the study of deep-seated movements and rearrangements that the fluids undergo incident to the drilling and operation of wells and to the factors and relationships governing these movements and rearrangements. This work is important because the recovery of oil and gas depends directly upon the movements of the fluids to the wells. The relative efficiencies of various methods of recovery under different sets of conditions and means of improving these methods are also being studied. The scope of this work is broad but it lies mainly within the provinces of geophysics and geochemistry together with their applications. These lines of field and laboratory investigation are so interrelated that sharp divisions between them are impossible. In the efforts that the Bureau of Mines is mak-

[12] Mills, R. V. A., Discussion of paper by R. O. Neal, "Petroleum Hydrology Applied to the Mid-Continent Field," *Transactions of American Institute of Mining and Metallurgical Engineers,* vol. 61, 1919.

ing to diminish underground losses and to develop more efficient methods of recovery, all three lines of investigation are necessary because very little progress has been previously made in the study of fundamental subsurface relationships.

SUMMARY.

To enumerate the various relationships indicated by the investigations herein described would require a longer paper than is appropriate at this time. Consequently in addition to the conclusions from the experiments the present contribution is summarized by a statement of a few of the broad facts and relationships that have been established.

One of the most important things to be realized is that all of the phenomena observed in the laboratory, as well as in the field, are brought about through the influence of various factors with differing effects. In other words, we are obliged to deal with the summations of the effects of many factors; not with the effect of any single factor. The values of the different factors that influence the migration, accumulation, mode of occurrence, and the recovery of oil and gas are extremely variable and are relative one to another. Different factors have predominating influences according to the different sets of limiting conditions into which enter, collectively, the porosities, fineness of pores, textural variations, and degrees of dip of the sands, the qualities of the fluids, more especially the viscosities of the oils, the degrees of saturation of the strata by water and oil, the temperatures, pressures, and many other conditions. Thus, it is recognized that there is a wide range of variation in the nature and extent of induced movements, especially the differential movements of gases, oils, and waters upon which recovery together with the effects of water upon recovery very largely depend. It is further recognized that gas mixed with oil facilitates lateral as well as vertical migrations of oil in water-bearing strata. Again, it is recognized that there may be a limit to the fineness of water-filled interstices beyond which viscous oils do not appear to migrate "gravitationally" under ordinary conditions.

It is further recognized that in a medium grained water-saturated sand (such as *b*, Table II.) a single globule of oil (such as 1, Table I.) fails to migrate "gravitationally" but as more globules of oil are added to it, there is formed an aggregation of globules whose *cumulative buoyancy* is sufficient to overcome the resistance to upward migration. Such relationships are important in the consideration of up-dip migrations. We must keep constantly in mind the critical conditions up to which certain phenomena hold true but beyond which there are absolutely different phenomena.

The field and laboratory investigations that the writer has so far made, indicate that under ordinary field conditions the up-dip migration of oil and gas under the propulsive force of their buoyancy in water, as well as the migration of oil, either up or down dip, caused by hydraulic currents, are among the primary factors influencing both the accumulation and the recovery of oil and gas.

The terms, "up-dip migration" and "down-dip migration," as used in this paper, apply to migrations that are in accordance with the configuration of the tops of the sands, regardless of actual structures. It must be remembered that there are many subsurface conditions such as the dome-like tops of lenses, irregularities in the tops of sands, and irregular textural barriers, which bear no consistent relations to structure, but whose influence upon oil and gas accumulation are analogous to those of true anticlines and domes. The writer's remarks apply to these conditions which he terms *structural analogies*.

In concluding this paper, the writer calls attention to the views recently set forth in the literature[13] that the migration and accumulation of oil in water-saturated strata are caused mainly by capillary forces; that oil does not migrate up the dip, due to the differences in specific gravity between oil and water; and that oil is not propelled through sands by hydraulic currents. It

[13] McCoy, A. W., "Notes on Principles of Oil Accumulations," *Jour. of Geology*, vol. 27, 1919, pp. 252–262.

Jones W. F., "The Relation of Oil Pools to Ancient Shore Lines," Economic Geology, vol. 15, 1920, pp. 81–87.

is further maintained that oil has been forced out of the fine bituminous shales adjacent to the reservoir rocks, by the capillary action of water and that no wide lateral movements of oil have subsequently taken place.

The writer can not accept these views as generalizations. They may appear to hold true under exceptional conditions, as in small scale laboratory experiments where the conditions of experimentation are especially favorable to the hypotheses, but they do not generally hold true, either in the laboratory or in the field. Capillary adjustments between oil and water in saturated strata are restricted within short lateral ranges, amounting to only a few centimeters in the writer's experiments. The principal rôle of capillarity, in saturated strata, is to retard rather than to promote fluid movements.

NEED FOR FURTHER EXPERIMENTATION.

Systematic and scientific experimentation upon subsurface problems in oil and gas fields, in conjunction with intensive field work, is imperative. It throws invaluable light upon the fundamental principles and relationships governing the occurrence, accumulation, and recovery of oil and gas, and opens the way for more intelligent and efficient subsurface conservation and recovery.

The necessity for this work is emphasized by the progressive depletion of our deposits of petroleum and natural gas under an ever increasing demand for these hydrocarbons. Hasty and wasteful field methods accelerate this depletion through enormous underground losses.

The utmost effort must be made to eliminate these losses. Producing fields must be conserved against premature abandonment. Development must be intelligently extended. Maximum ultimate yields, with profit, must be obtained, and oil left underground by wasteful methods in old and abandoned fields must be recovered. Under the stimulus of the rising prices of oil, these things can be done profitably through scientific methods of work in which petroleum experimentation must play an important part. If they

are not done the consequence will be a disastrous waste of invaluable resources.

ACKNOWLEDGMENTS.

For valuable suggestions and encouragement during his field and laboratory investigations, the writer is indebted to his colleagues in the Bureau of Mines, more especially to J. O. Lewis and C. H. Beal, whose vast stores of information and keen insight into subsurface problems have proven invaluable; and to the conscientious, painstaking, efforts of Mr. E. C. Lane, who assisted both in the development of the apparatus and in the experiments. Grateful acknowledgment is also made to the many companies, individual operators, and employes who co-operated with, and assisted, the writer in the Appalachian, Mid-Continent, and California fields.

U. S. BUREAU OF MINES, WASHINGTON, D. C.

ECONOMIC GEOLOGY AND STRATIGRAPHY OF THE GUNFLINT IRON DISTRICT, MINNESOTA.

T. M. Broderick.*

CONTENTS.

	Page.
Introduction	422
Part I. General Geology	423
General Features	423
Succession of Rocks	424
General Description of Upper Huronian	425
Basal Quartzite	425
Gunflint Iron-bearing Formation	426
Detailed Stratigraphy	428
Correlation with Biwabik Formation	435
Structure	437
Origin and History	439
Metamorphism	440
Texture and Mineral Composition	440
Thickness	441
Rove Slate	442
Keweenawan Intrusives	442
Part II. Iron Ores of Gunflint Region	444
Hematite and Siderite	445
Magnetite Concentrating Ore	445
Comparison with East Mesabi Magnetites	449
Summary	450
Part III. Application of Detailed Stratigraphy to Pre-Cambrian Correlation	450

INTRODUCTION.

The recent activity of Hayden, Stone and Company in experimental work to determine the possibility of concentrating the fine-grained magnetite of the eastern Mesabi has led to a consideration of the availability of other Lake Superior deposits of low grade magnetite bearing rock for magnetic concentration. Within a few miles east of the quarry site selected by those inter-

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ested in the east Mesabi deposits, the ore formation is cut off by the Duluth Gabbro. Sixty miles northeastward, in the vicinity of Gunflint Lake, it emerges again and extends into Canada. Naturally the question arises as to the nature of the formation in this area, and the possibility of mining and concentrating it at a profit.

Since it was found that field study on the eastern Mesabi was successful in making a subdivision of the Biwabik formation which limited the ore best adapted to concentration to certain horizons,[1] the writer with Mr. Gruner was sent into the Gunflint Lake country for several weeks by the Minnesota Geological Survey, to make a similar study. The chief objects of the work were to determine whether or not the subdivisions of the Biwabik formation of the Mesabi persisted in the Gunflint formation; to add to the knowledge of the structure of the formation; and to study the formation from the standpoint of the possibility of magnetic concentration, with sampling of favorably appearing horizons for test runs. Although the time allowed for the work was rather short, the main objects of the trip were accomplished.

PART I. GENERAL GEOLOGY.

General Features.

The Gunflint area is situated in Townships 65 N., Ranges 4 and 5 W., in the northwestern part of Cook County, Minnesota, its eastern boundary being Gunflint Lake, which is part of the Minnesota-Ontario boundary waters. It extends westward for about 8 miles, where the iron formation is cut off by the Duluth gabbro. The area where the iron formation outcrops is marked by gentle slopes to the south, broken by steep northward-facing cliffs, some of them a hundred feet or more in height. These cliffs are capped by diabase sills or by the more resistant cherty beds of the iron formation. A pre-glacial valley, which cuts

[1] Broderick, T. M., "Detail Stratigraphy of Biwabik Iron-bearing Formation, East Mesabi, Minnesota," ECON. GEOL., vol. 14, pp. 441–451, 1919.

Grout, Frank F., "The Nature and Origin of the Biwabik Iron-bearing Formation of the Mesabi Range, Minnesota," ECON. GEOL., vol. 14, pp. 452–464, 1919.

across the east-west ridges, is a prominent feature in Secs. 22 and 27. In most of the area outcrops are abundant.

A few old claim shanties, the fallen-in log buildings of the abandoned Paulson Mine (Fig. 52) and overgrown wagon roads speak of a considerable activity. Every year the area is visited by men interested in the possibilities of the development of the iron ore.

The area is reached by weekly railroad service from Port Arthur, Ont., to North Lake, Ont., which is about 14 miles from the west end of Gunflint Lake, or, it may be just as convenient to go in by canoe from Winton, Minnesota, which is about 3 days' journey. Another way in is from Grand Marais, by an old county road.

Succession of Rocks.

The succession of rocks in the Gunflint district is as follows:

Quaternary System	
Pleistocene series	Drift
Unconformity	
Algonkian system	
Keweenawan series	Duluth gabbro and Logan sills
Unconformity	
Huronian series	
Upper Huronian (Animikie group)	Rove slate Gunflint formation (iron-bearing)
Unconformity	Quartzite member
Lower Middle Huronian	
Unconformity	Graywacke with acid and basic intrusives
Archean system	
Laurentian series	Saganaga granite intrusive into the Keewatin
Keewatin series	Green schists, greenstone

The present paper is concerned chiefly with the rocks of the Upper Huronian group, and the igneous intrusives of Keweenawan age. The others are mentioned briefly, and for a more

detailed description of them the reader is referred to earlier publications.[2]

General Description of Upper Huronian.

In the Gunflint district the Upper Huronian consists of three members, a lower quartzite, overlain by the Gunflint iron formation and the Rove slate. These are correlated with the Pokegama quartzite, the Biwabik iron formation, and the Virginia slate of the Mesabi range. Just as the gabbro cuts across the Upper Huronian on the east Mesabi, overlapping the upper beds first from west to east, so it cuts across the Upper Huronian in the Gunflint district, overlapping successively the upper and lower beds from east to west. The iron formation first appears in Sec. 34, T. 65 N., R. 5 W., widening out gradually toward the east, until in the western part of Sec. 27, T. 65 N., R. 4 W., all the beds of the Gunflint are present and Rove slate appears. This in turn widens out toward the east, there being a thickness of many thousands of feet some distance east of the limits of the Gunflint district. The structure of the Upper Huronian is monoclinal, dipping at various angles to the south. The beds are intruded by diabase sills and dikes and by the Duluth gabbro. They lie unconformably upon the Lower Huronian and Archean rocks.

Basal Quartzite.

At the base of the Upper Huronian, there is in many places a conglomerate, made up of pebbles of the underlying formations and vein quartz. In Secs. 22, 23, and 24, this conglomerate grades upward into a fragmental quartzite. In much of the previous literature on the Gunflint and eastern Mesabi districts, the term "quartzite" is used to designate the entire thickness of iron formation in the vicinity of the Duluth gabbro, where it has been recrystallized into a rock consisting of a large proportion of coarse quartz grains. The probable origin of most of this quartz

[2] Grant, U. S., Final Report Minn. Geol. and Nat. Hist. Survey, vol. 4, pp. 462–480, 1898.

Van Hise, C. R., and Leith, C. K., U. S. Geol. Survey Mon. 52, pp. 198–204, 1911.

is by metamorphism of chemically precipitated silica, as a result of the heat and pressure developed during the intrusion of the gabbro. Very little of it is of clastic origin. The word quartzite is used in this paper to designate a rock made up largely of clastic quartz grains with a quartz cement. Such a basal member of the Upper Huronian corresponding to the Pokegama quartzite of the Mesabi range, has been thought to be entirely lacking in the Gunflint district. In the sections mentioned above, there is a lens of such material which reaches a thickness of at least 10 feet in Sec. 23. It is made up largely of fairly well sorted rounded quartz grains, enlarged by secondary growth. Some of it has a greenish tinge, due to a small proportion of chlorite between the grains. The quartzite lies upon the Saganaga granite, the contact being marked in most places by a thin basal conglomerate with more or less greenish shaly material.

Gunflint Iron-bearing Formation.

Introduction.—Conformably above the quartzite is the Gunflint iron-bearing formation. The lower beds of the formation first appear in Sec. 34, T. 65 N., R. 5 W., extending eastward for a distance of 6 miles in a belt averaging less than one quarter of a mile in width. Thence from the Paulson mine eastward for a mile, the belt widens, due to a flattening of the dip and to folding. The width of outcrop becomes less again toward Gunflint Lake (Fig. 52).

The different horizons of the Gunflint formation subdivided and compared with the divisions of the Biwabik formation of the Mesabi range is of interest. Wolff[3] has divided the Biwabik formation of the main Mesabi into four large divisions which he recognizes in all parts of the range. They are called cherty or slaty beds according to whether they are massive siliceous taconite or thin bedded taconite. Thus the lower part of the formation is called the Lower Cherty beds, and this is overlain in turn by the Lower Slaty, the Upper Cherty, and the Upper

[3] Wolff, J. F., "Recent Geologic Developments on the Mesabi Iron Range, Minnesota," *Am. Inst. Min. Eng. Trans.*, vol. 56, p. 142, 1916.

FIG. 52. Map of the eastern end of the Gunflint area, Cook County, Minn.

Slaty beds. In 1917 the Minnesota Geological Survey extended this subdivision through the eastern end of the range,[4] adhering to the main divisions described by Wolff, and the persistence of the main divisions of the Biwabik formation for a distance of one hundred miles along the strike has been recognized. Although it seemed reasonable to expect that the Gunflint formation, only 60 miles from the eastern Mesabi, should show somewhat the same stratigraphy as the Biwabik, if previous correlations of the two formations were correct, the writer was surprised to find a remarkable similarity, even in minor details, between the formations in the two districts.

Detailed Stratigraphy.—The following tabulation shows in brief the chief characteristics of the Gunflint iron-bearing formation.

TABLE OF GUNFLINT IRON-BEARING FORMATION.

	Thickness.
Top—Rove slate.	
Gunflint iron-bearing formation.	
D. Upper Slaty beds.	
No. 3. Limestone with silicates, practically no magnetite....	10 feet
No. 2. Thin bedded quartz amphibole carbonate rock with graphitic slate in thin layers, alternating with bands of almost pure cherty silica averaging 1 to 2 inches in thickness. From 5 per cent. to 10 per cent. magnetite.	140 feet
No. 1. Similar to No. 2, with thicker and more lenticular cherty beds, some with white quartz septaria. 5 per cent. to 10 per cent. magnetite.	
Entire Upper Slaty, drag folded and intruded by Pre-Gabbro diabase sills.	
C. Upper Cherty beds.	
No. 2. Massive gray cherty beds with algal structures in middle. Little magnetite, but some conglomerate in places. Beds of rich magnetite a few inches in thickness above and below the algal structures....	20 feet
No. 1. Wavy lenticular gray cherty beds, little conglomerate, thin beds of magnetite becoming more frequent downward. Less than 20 per cent. magnetite.....	25 feet
B. Lower Slaty beds.	
No. 3. Thin bedded, fine grained, cherty amphibole magnetite rocks; 25 per cent. to 35 per cent. magnetite.....	45 feet

[4] Broderick, T. M., *op. cit.*

No. 2.	Massive cherty beds with a few slaty seams. Bottom 8 feet marked by bands of white quartz and green amphibole. Little magnetite	25 feet
No. 1.	Black thin bedded slate; little magnetite	10–25 feet
A. Lower Cherty beds.		
No. 3.	Massive cherty beds, poorly exposed; about 20 per cent. magnetite	10–20 feet
No. 2.	Massive cherty amphibole magnetite rock; about 50 per cent. to 60 per cent. magnetite	5–15 feet
No. 1.	Basal beds, conglomerate, shale, massive chert with algal structures common	0– 5 feet

Bottom—Saganaga granite, Lower Huronian slate and conglomerate or Upper Huronian quartzite.

A. Lower Cherty Beds.—Bed No. 1 in most places observed is but a few feet in thickness and contains more or less conglomeratic material. It is well exposed on a low ridge just to the west of the line between Secs. 23 and 24 (Fig. 52), along the contact with the underlying quartzite. Here it is composed largely of cherty fragments in a cherty groundmass. Structures which have been ascribed to algal origin are common in this bed, although they lack the regularity of those of the East Mesabi. Granules of the shapes and size of the greenalite granules of the Biwabik formation are not uncommon. No greenalite was noted, the granules now being made up of quartz, amphibole, and magnetite. Where the conglomerate lies directly upon the Archean, as in Sec. 27, it is made up of fragments of quartz and green schist, with more or less shaly material.

Bed No. 2 is the horizon of extensive exploration and development. The evidence gained from diamond drilling, pits, shafts, and the present study of the formation, bed by bed, makes it certain that this is the richest horizon in the formation. Assays have been published showing iron contents around 60 per cent. These high percentages do not represent any considerable thickness, however, and they undoubtedly include the iron in minerals other than magnetite. The greatest thickness seen by the writer (Sec. 23) was 12 feet. This was found to contain 38.23 per cent. iron in the mineral magnetite.[5]

[5] From a sample turned over to the Minn. School of Mines Expt. Sta. for magnetic concentration test.

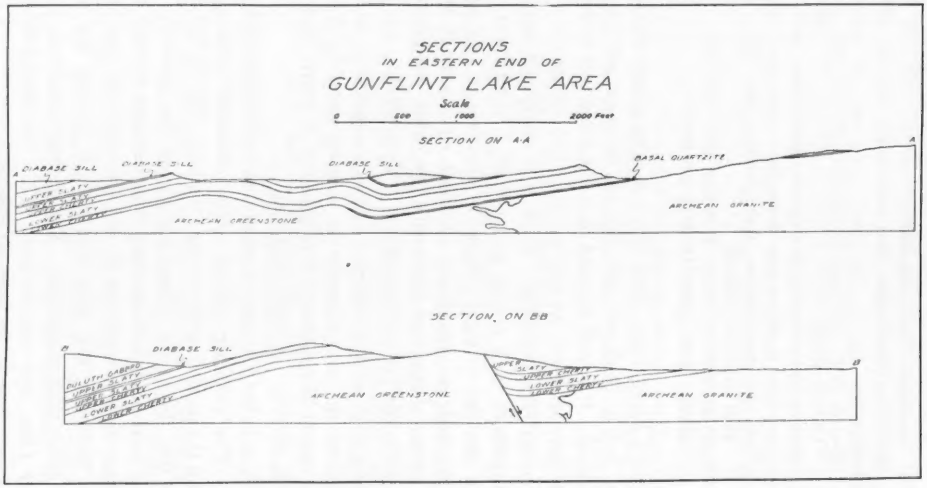

FIG. 53. Cross sections of the Gunflint district.

The best exposures of the bed are in Sec. 23, where it is a rather massive thick bedded magnetite rock with subordinate quartz and amphiboles. It is comparatively coarse grained; the silicates in many cases appearing as spots one quarter of an inch in diameter.

Bed No. 3 is not well exposed in the area. It is known chiefly from drill cores, and may be regarded as an upward gradation of bed No. 2 with a considerable drop in magnetite content, leaving the quartz and silicates as the predominant minerals.

The Lower Cherty beds have been intruded by diabasic and gabbro dikes, but no sills were noted in them.

B. Lower Slaty Beds.—Above the Lower Cherty beds lies a thin-bedded, black, graphitic slate (Bed No. 1) which forms the base of the south wall of the valleys which lie along the junction of the Lower Cherty and Lower Slaty beds. Such valleys cross the southern parts of Secs. 21 and 22, and the north halves of 23 and 24. The valley in the western part of which the Paulson mine is located (Figs. 52–53) is also in these softer beds. No pronounced secondary cleavage is developed in this rock, but it breaks easily parallel to the bedding. The entire thickness of these beds was not measurable in the outcrops. Drill cores of holes in the vicinity of the Paulson mine and westward show it to be about 10 feet. Eastward across Secs. 22, 23, and 24, it is probably greater, the maximum being about 25 feet. The magnetite content is low.

Bed No. 2 is of the massive cherty type which characterizes the Upper Cherty beds and would be mapped as such were it not for the fact that it lies between beds 1 and 3, both of which are slaty in character. The bottom 8 feet of this bed is marked by bands of white quartz and green amphibole. The upper part is made up of a dense gray cherty rock, with occasional thin wavy seams containing more amphibole and magnetite than the rest. This bed is well exposed in Secs. 27 and 22. It is about 25 feet in thickness and contains little magnetite, but grades upward into bed No. 3 by increase in the number of thin slaty seams richer in magnetite.

Bed No. 3 is a thin bedded, bluish or greenish black rock with a marked cleavage parallel to the bedding. The beds are exceedingly thin, many being .1 mm. and less. They are persistent, uniform in thickness, and form marked contrast to the lenticular beds which are common in other parts of the formation. The predominant minerals are quartz, amphibole, and magnetite, but while the magnetite content is fairly high, the exceedingly fine-grained texture makes the problem of magnetic concentration difficult. The thickness is about 45 feet.

No diabase sills were noted in the Lower Slaty beds, but there are a few basic dikes.

C. Upper Cherty Beds.—There is no sharp division between the Upper Cherty beds and the Lower Slaty. Massive cherty beds appear in the top of bed No. 3 of the Lower Slaty horizon, and within a few feet above become predominant, the thin-bedded, magnetite-rich layers becoming fewer and further between. The rock is gray in color and consists predominantly of quartz. The thinner magnetite layers, which are wavy and irregular, divide the rock into long lenticular beds. The total magnetite content of bed No. 1 is low, being probably less than 15 per cent. The size of grain is coarse as compared with the Slaty beds, although thin sections show considerable fine cherty material, with a few of the granule forms. Very little material of clastic origin was seen. The conglomeratic texture which characterizes the Upper Cherty of parts of the Eastern Mesabi is lacking in this bed. The thickness as measured in Sec. 22 is 25 feet.

Above bed No. 1 is about 20 feet of similar material which is even more massive than bed No. 1. The beds are thicker and the seams rich in magnetite are fewer. The average magnetite content is probably less than 10 per cent. In the midst of this bed is found a horizon up to 5 feet in thickness which is conspicuous because of peculiar markings. Narrow black lines appear on the weathered surfaces which curve and twist into forms variable in shape and size. In some places they are parallel to the bedding, and would be classified as bedding if it were not for the many

odd contortions that they show. In both horizontal and vertical cross sections they are seen to curve around and double back on themselves, assuming forms that can not be explained as being the results of deposition cross bedding, or of folding. In some cases they form concentric shells about magnetite pebbles, or quartz amphibole magnetite granules. Such concentric forms may be seen around cherty masses several feet in diameter. Coming as they do at the same horizon as the structures thought to be of algal origin at the top of the Upper Cherty in the Eastern Mesabi district, they are assigned to the same mode of origin, although they lack to a large extent the more uniform shapes and size shown by those of the Mesabi range. Immediately associated with these structures in the Gunflint formation is the only marked conglomerate of the Upper Cherty beds. The pebbles are mostly less than one half inch in diameter and are made up of chert or magnetite. In some places there is an abundance of rounded fragments having the same algal structures as the matrix, showing that the structures were formed and broken before the deposition of the next bed.

Granule forms are not uncommon, the rounded and crescentic shapes being preserved, although the greenalite which is thought to have been the original material of the granules has been replaced by quartz, amphibole and magnetite. These minerals are the most abundant ones, in the order named, of the bed as a whole.

Here and there, immediately above and below the algal structures, may be found a few inches of almost pure magnetite. The hematite which marks this horizon on the East Mesabi was not found in the Gunflint region. West of the Paulson mine, where the proximity of the Duluth gabbro has caused extensive recrystallization, the structures are not to be found, but east of the Paulson, one may follow the top of the ridge of iron formation for over half a mile, walking on an almost continuous exposure of the algal structures. The outcrops of Upper Cherty beds in Secs. 22 and 23 are commonly of this algal horizon, as it is very resistant to erosion. The thinness of this bed, its persistence, and

its many exposures made it the most valuable horizon marker in the district.

Diabase dikes cut the Upper Cherty beds in several places, but no sills were found in them.

D. Upper Slaty Beds.—The Upper Slaty beds outcrop in the folded portion of the area, and have been intruded by diabase sills and dikes of varying size. The characteristics of the beds can be observed and general subdivisions made with a fair degree of certainty, but measurements of thickness are subject to considerable error.

As a whole the Upper Slaty beds show a predominance of fine-grained, thin-bedded rock. The mineral composition is not different from that of the Cherty beds, that is, largely quartz and amphibole, with some magnetite. The difference is in the finer-grained texture and the thin beds. The lower beds of the Upper Slaty are characterized by the frequent lenticular cherty layers between the thin bedded slaty material. In these cherty lenses are occasional conglomerate pebbles, and in about six outcrops in the area studied, septaria with white quartz filling the cracks were seen. The area of each septarium was less than 1 square foot. Above these "septaria" beds the lenticular nature is not so pronounced and the formation is made up of parallel layers of thin bedded graphitic quartz amphibole rock, alternating with thicker beds of very fine grained chert. Quartz grains .001 mm. in diameter are common in these cherty layers. Such layers are not lenticular, but extend some distance parallel to the other beds. They are in general less than 2 inches in thickness. In many places, especially near the top of the formation, there is more or less calcite present. Thin sections show the presence of secondary silicates developed from the carbonate, such as diopside and actinolite. The magnetite content of the Upper Slaty beds is probably less than 10 per cent. No especially rich horizons were found. The Upper Slaty beds can be seen in good exposures across the south half of Sec. 23. The gabbro begins to cut across them in Sec. 27, and therefore they become thinner westward. The thickness as estimated from cross sections is about 140 feet.

At the top of these two lower members of the Upper Slaty beds is Bed No. 3. This is principally a carbonate rock, largely calcite. Secondary silicates are abundant and the grain is rather coarse, due to a thick diabase sill which follows it. This limestone is but 10 feet in thickness, and occurs in the southeast corner of Sec. 23.

Correlation with the Biwabik Formation.—The propriety of correlating the Gunflint iron-bearing formation with the Biwabik formation of the Mesabi range is no longer questioned. The most recent detailed studies of the region lead to the conclusion that both formations are the middle member of the Upper Huronian or Animikie group.[6] The principal bases upon which this correlation has been made are:

1. They are both unconformably above the Lower-Middle Huronian series.

2. They are conformably overlain by a thick slate formation.

3. Although there is no direct connection between the two because of the truncation by the Duluth gabbro, numerous inclusions of the iron formation near the base of the gabbro in the sixty-mile gap between outcrops in place are suggestive of the former continuity of the formation.

When one compares the two formations, bed by bed, there can be no doubt as to the accuracy of the correlation. The following points of similarity of the Gunflint formation and the Biwabik on the east Mesabi are to be noted.

1. The general divisions into Upper and Lower Cherty and Upper and Lower Slaty are easily made in each case.

2. Conformably below the iron formation and unconformably above the older rocks is a thin quartzite in some places.

3. At the base of the iron formation is a thin conglomerate.

4. Toward the base of the Lower Cherty is a bed of comparatively rich magnetite ore.

5. Above this is a lean cherty bed, showing algal structures on the east Mesabi, but not sufficiently exposed in the Gunflint area

[6] Grant, U. S., *op. cit.*
Van Hise, C. R., and Leith, C. K., *op. cit.*

to determine whether such structures exist. The bed is known to be present, however, from drill cores which are too small to show algal structures the size of those at this horizon on the east Mesabi.

6. At the base of the Lower Slaty lie the lean thin beds known over the Mesabi range as the "Intermediate Slate."

7. Above the intermediate slate lies a lean massive cherty bed.

8. Near the top of the Upper Cherty beds are found the peculiar structures ascribed to algal growth.

9. These beds showing algal structures have more conglomeratic material than any other part of the formation excepting the basal conglomerate.

10. Above and below the conglomeratic algal beds on the east Mesabi occurs about 10 feet of exceptionally rich magnetite beds, In a few scattered places along the outcrops of the algal beds in the Gunflint area, are patches of almost pure magnetite one or two inches thick. They would probably have been overlooked as not worthy of mention, had it not been for the fact that the writer was looking for the equivalent of the rich beds in a similar horizon on the east Mesabi.

11. White quartz septaria are conspicuous in almost any outcrop of the lower beds of the Upper Slaty horizon on the East Mesabi. These septaria are not nearly so numerous in the Gunflint formation, but they are present in the same place stratigraphically as on the east Mesabi.

12. The only notable drag folding on the east Mesabi is in the Upper Slaty beds. Here the size of the folds is in general small. In the Gunflint region the Upper Slaty beds show close folding over the greater part of the area in which they outcrop.

13. The upper parts of the Upper Slaty beds have increasing amounts of carbonate.

14. The Upper Slaty beds are intruded by numerous diabase sills.

15. The top of the Upper Slaty beds is a thin layer of amphibolitic limestone.

16. Conformably above the iron formation in each district lies a great thickness of slate.

The chief points of dissimilarity of the Gunflint and the Biwabik formation of the east Mesabi are that most beds of the Gunflint are decidedly lower in magnetite than the corresponding beds on the east Mesabi; the Lower Slaty division of the Gunflint contains a magnetite rich bed not represented on the east Mesabi; and the Upper Cherty division, notable for its magnetite content on the east Mesabi, is decidedly lean in the Gunflint. These differences do not affect the general correlation, however, because within a distance of 7 miles on the east Mesabi, the Upper Cherty beds become decidedly leaner and show much less conglomerate, while the thickness of rich magnetite in the Lower Cherty beds increases from a few feet up to fifty.

Structure.—The structure of the Gunflint formation is monoclinal. The strike is in general a little north of east and the dip is to the south, excepting on the limbs of minor folds. Dips of 45° to 60° are common in the western end of the district; east of the Paulson mine it averages about 10° to 12°.

The outcrops of horizon markers and their dips indicate that in the eastern end of the district there are repetitions of the various beds, some of which are explainable by folding, others being more likely due to faulting. Some of the dips vary in short distances from 0° to vertical, and from north to south. The beds show considerable contortion. It is noteworthy that all these contortions are in the Upper Slaty beds where considerable brecciation of the cherty material took place, and the slaty carbonate parts flowed around the angular chert fragments. It seems unlikely that the entire formation was as closely folded as were these Upper Slaty beds.

The writer observed no evidence of such close folding in the massive cherty beds or in the diabase sills. It has been suggested that these contortions are due to the intrusive action of the diabase.[7] Inasmuch as the diabase itself (above the contorted horizons) and the Upper Cherty beds (below them) have been subjected to gentle folding, it is here suggested that the Upper Slaty beds between them suffered the usual drag folding of incompetent

[7] Clements, J. Morgan, U. S. Geol. Survey Mon. 45, p. 377, 1903.

beds. Figs. 52 and 53 have been constructed on this supposition, which agrees with the areal distribution of the various members of the Gunflint formation.

There are other irregularities in the distribution of the horizon markers which are best explained by faulting. For instance, the upper beds of the Upper Cherty horizon are found capping a hill just north of the center of Sec. 27, at an elevation of 1,860 feet, and the same beds are found a quarter of a mile to the northeast, across the ancient north-south valley at an elevation of 1,660 feet. With a nearly east-west strike, and a dip to the south of about 12° to 15° in each outcrop, the situation is the reverse of what it should be, *i.e.*, the lower outcrop should be to the south instead of to the north of the higher outcrop. The evidence points to the absence of any folding which would explain such conditions. A similar case occurs just to the north near the center of Sec. 22, where all previous maps show the base of the Upper Huronian turning suddenly to the north across a level swamp. Such a change in strike has not been observed. Both these anomalous conditions can be best explained by a normal fault trending along the abandoned north-south valley, the eastern side having a vertical drop of 130 feet (this being the stratigraphic thickness between the Upper and Lower Cherty horizons).

Extending across the SE.¼ Sec. 21, and the SW.¼ Sec. 22, is a belt of iron formation surrounded by Archean greenstone which has been described as an infolded syncline.[8] From the distribution and attitude of the outcrops it seems likely that there is a fault along the south side of this syncline. In all cases noted the outcrops of iron formation nearest the greenstone on the south limb of this syncline are of the upper horizons of the iron formation, rather than the lower. Higher horizons occur to the east than to the west along this infolded strip, making it appear as though the older greenstone cut across the beds of the iron formation. These facts seem to favor the existence of a fault along the southern edge of the strip and the writer has mapped

[8] Grant, U. S., *op. cit.*, p. 472.
Clements, J. Morgan, *op. cit.*

it as such (Figs. 52 and 53), although it is recognized that there is sufficient space between all the outcrops of greenstone and upper beds of iron formation for the lower beds to occur if they were suddenly upturned.

Origin and History.—The main events in the geological history of the Lake Superior iron formation are well known, namely, sedimentation in relatively shallow water. The material was largely precipitated from solution, and consisted of chert with varying amounts of ferrous silicate, ferrous carbonate, and hydrous iron oxides. Very little clastic material was in the primary deposit. Some horizons were laid down much richer in iron than others. The greater part of the Lower Cherty horizon of the Biwabik formation owes its high iron content to primary deposition. On the other hand, certain other beds have probably undergone a primary enrichment due to the operation of oxidation and leaching processes shortly after deposition, at times of lowering or temporary withdrawal of the sea.[9] Such periods of primary enrichment are marked by more or less conglomeratic material. Sufficiently detailed work to determine the extent of erosion during these periods has not been done in most places. Grout classifies the conglomerates of the Biwabik as intraformational, not marking any erosional unconformity.[10] Hotchkiss, by frequent measurement of sections of the Ironwood formation of the Gogebic, finds that at least one of the conglomerates marks an unconformity.[11] In any event, enrichment has played a subordinate part in the Gunflint iron formation. The two important iron beds, one in the Lower Cherty, and the other in the Lower Slaty member, show no evidence of enrichment. A little conglomeratic material at the top of the Upper Cherty beds marks no noticeable enrichment, or erosional unconformity, as far as could be discovered.

[9] Grout, Frank F., "The Nature and Origin of the Biwabik Iron-bearing Formation of the Mesabi Range, Minnesota," ECON. GEOL., vol. 14, pp. 458–463, 1919.

[10] *Idem.*

[11] Hotchkiss, W. O., "Geology of the Gogebic Range and its Relation to Recent Mining Developments," *Eng. and Min. Jour.*, vol. 108, p. 506, 1919.

Metamorphism.—After deposition and deep burial, the iron formations of the Lake Superior region were subjected to more or less folding and igneous intrusion. It was during these pe iods of static, dynamic, and contact metamorphism that the primary minerals of the formation reacted to form the silicates and magnetite which are characteristic of the unweathered formations of some districts. In the past, dynamic and contact metamorphism have been emphasized as the chief processes involved in the formation of the magnetite rocks of the Lake Superior iron ranges. That magnetite may develop under conditions of static metamorphism, with no more dynamic action than is involved in a gentle tilting of the beds, may be seen in the Biwabik and the Gunflint formations. Thus, drill cores of the unoxidized Biwabik formation, far from any igneous intrusives, show that the chief iron-bearing mineral now is magnetite.[12] Greenalite is practically limited to comparatively narrow parts of the slaty horizons, and hematite is rare indeed. Likewise in the Gunflint area, it is not believed that the action of the Duluth gabbro had any effect on the amount of magnetite present in a given horizon. For instance, the magnetite rich beds of the Lower Slaty horizon were sampled in Sec. 28, where the gabbro is close by, and Sec. 22, where it is farther away (*i.e.*, stratigraphically near or far) and the two samples had the same percentage of magnetite within the limits of sampling error.[13] Apparently, then, the effect of the gabbro in the Gunflint region was the same as on the east Mesabi; it promoted coarse crystallization and reduced pore space, but probably did not increase the amount of magnetite. The type of silicate present was controlled partly by the influence of the gabbro. For instance, the development of fayalite in both the Gunflint and Biwabik formations and the cordierite reported by Zapffe seem to be limited to the coarsely crystalline iron formation in the vicinity of the gabbro.

Texture and Mineral Composition.—There is evidence of some

[12] Wolff, J. F., "Recent Geologic Developments on the Mesabi Iron Range, Minnesota," *Proc. Lake Sup. Min. Inst.*, 1917, p. 234.
Grout, Frank F., *op. cit.*, p. 463.

[13] Analyses made by the Minnesota School of Mines Experiment Station.

contribution of material from the gabbro to the nearby intruded rock. The magnetite rich horizon of the Lower Cherty beds shows a considerable amount of sulphide from the Paulson mine westward, whereas, in the eastern part of the area, the same horizon shows little if any. The TiO_2 content of the magnetite of the same horizon at the Paulson is .09; while in Sec. 23 it is .03. The TiO_2 content of the Lower Slaty member at the Paulson is .21; in Sec. 22 it is .16. Inasmuch as the gabbro is much nearer stratigraphically at the Paulson, the additional sulphur and titanium are probably contributions from it.

The present mineral composition of the Gunflint beds has been mentioned under the description of the separate horizons. Probably over 95 per cent. of the formation is quartz, amphibole, and magnetite, most abundant in the order named. Carbonate has been mentioned as characterizing the beds in the region of Gunflint Lake. This impression possibly results from the fact that the upper part of the Upper Slaty beds which are the highest in carbonate content, outcrop over a wider area near Gunflint Lake than elsewhere. Westward, the gabbro comes into direct contact with the iron formation and there is a consequent enlargement in the size of the grain. None of the fine grained chert remains, and the rock is conspicuous for its coarse bands of fairly well-segregated quartz, amphibole, and magnetite, together with many silicates which characterize the contact zone.[14]

Thickness.—The thicknesses of the three lowest members were obtained by measuring the excellent sections exposed in the cliffs. The thickness of the Upper Slaty is not so certain, as the exposures are not so complete. The following figures are believed to be close to the true thickness.

[14] Zapffe, Carl, "Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," ECON. GEOL., vol. 7, p. 175, 1912.

Zapffe's paper deals with the intensely metamorphosed iron formation of the western part of the district, where the gabbro is in direct contact with it. The various subdivisions which are recognized in the area herein described (Fig. 52) are recognized only with difficulty in the western area which supplied the material studied by Zapffe. Certain horizons, however, such as the "intermediate slate," may be picked out in drill cores even from the most intensely metamorphosed iron formations.

Upper Slaty	150 feet
Upper Cherty	45
Lower Slaty	95
Lower Cherty	40
Total thickness of the Gunflint formation	330 feet

While this measurement is much less than the former estimates, ranging from 800 to 1,000 feet, it agrees well with the measured thickness of the Biwabik formation on the east Mesabi just before it begins to be truncated by the gabbro. The measurements referred to are as follows:

Upper Slaty	90 feet
Upper Cherty	95
Lower Slaty	85
Lower Cherty	70
Total thickness of Biwabik formation east of Dunka River	340 feet

Rove Slate.

The Rove slate lies conformably above the Gunflint iron formation, the contact being marked by a thin bed of limestone. The largest diabase sill in the area, possibly 150 feet in thickness, is intruded along this contact. Grant[15] has described these slates in some detail, and the writer will not discuss them in this paper. The gabbro truncates them, the last outcrop toward the west seen by the writer being at the base of the gabbro cliff south of the Cross River along the east line of Sec. 27. Here they are so altered as to be almost unrecognizable.

Keweenawan Intrusives.

The Keweenawan rocks in this area are the Duluth gabbro and the Logan sills. Dikes of diabase and gabbro are also of common occurrence. These are all intrusive into the Upper Huronian.[16] The map (Fig. 52) shows the Duluth gabbro, and the two largest diabase sills. Geologists agree that the relation of the Logan

[15] Grant, U. S., *op. cit.*, p. 475.

[16] The evidence of this relation is given in the publications of the Minnesota and United States Geological Surveys.

sills to the Duluth gabbro has never been satisfactorily stated. It has been pointed out that the gabbro and the sills are petrographically the same, the mineral composition being alike, and textural gradations within the sills showing all intermediate types ranging from the characteristic fine to medium grained diabase to gabbro. Van Hise and Leith conclude that the Logan sills and the Duluth gabbro are to be "regarded as essentially contemporaneous and genetically related."[17] Grant, after summarizing points of difference between the sills and the gabbro, says that he "is inclined to the idea that they are of earlier age than the gabbro."[18] One fact that has not been sufficiently emphasized, and which justifies the idea that the sills are earlier than the gabbro is that they have been metamorphosed by the gabbro, forming a hornfels. The diabase texture has been lost entirely in some cases, the minerals remaining essentially the same. The change tends to produce a fine to medium grained rock of the mineral composition of gabbro, a characteristic feature being that the grains of the various minerals are rather uniform in size, with a tendency toward rounded outlines.[19] Grant has shown such rocks to be present within the gabbro mass along its northern border.[20] They have frequently been confused with the slates and Archean greenstone, which where metamorphosed by the gabbro, either in the immediate contact zone or as inclusions in the gabbro develop to same hornfels texture. Since the diabase sills in the Upper Huronian in both the eastern Mesabi and the Gunflint region have suffered the same sort of change in the immediate vicinity of the gabbro, it is certain that they are somewhat earlier, perhaps of the same age as the "granulitic gabbro" described by Grant, and regarded by him as being earlier consolidations of the Keweenawan instrusive.[21] Not only do the

[17] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 202.

[18] Grant, U. S., *op. cit.*, pp. 487–488.

[19] Zapffe, *op. cit.*, p. 153, refers to this change as endomorphic. That the change is due to contact metamorphism by the Duluth gabbro is indicated by its confinement to the immediate contact one. Distant from the gabbro the sills are comparatively fresh and unaltered.

[20] Grant, U. S., *op. cit.*, pp. 477–478.

[21] Grant, U. S., *op. cit.*

diabase sills present this evidence of metamorphism by the Duluth gabbro, but sills of gabbro itself show the same changes. Thus we may say that the sills of diabase and gabbro in the Upper Huronian of the east Mesabi and the Gunflint region were of earlier age than the Duluth gabbro.

Localities where the metamorphic effects of the Duluth gabbro on the sills may be seen are as follows:

East Mesabi District.—Sec. 35, T. 61 N., R. 12 W.—SE. ¼ of NW. ¼ along west boundary of the gabbro.

Gunflint District.—Finer grained edges of gabbro sills in iron formation from Sec. 29, T. 65 N., R. 4 W. westward.

Good examples may be seen in some of the inclusions of Gunflint formation within the gabbro itself. Some such inclusions have sills in them, and after being broken off and surrounded on all sides by the gabbro magma, suffered intense metamorphism. The southern edge of the patch of Gunflint formation south of Gabimichigama Lake, in Sec. 7, T. 64 N., R. 5 W., contains such a sill, which, though it has lost its diabasic texture, is easily recognized as having been such from its relation to the iron formation, and the characteristic phenocrysts of plagioclase which remain.

PART II. THE IRON ORES OF THE GUNFLINT REGION.

Introduction.

The present plans for quarrying and concentrating the magnetic-rich beds of the Biwabik formation of the east Mesabi naturally arouse interest in the possibilities of a similar operation on what may be regarded as an extension of the Mesabi in the Gunflint Lake area. Economically considered, there are several factors which are the same in both areas. Among these are the attitude of the beds, in each case allowing quarry operations in part of the areas, and the fact that the chief iron ore mineral is magnetite, allowing magnetic concentration methods to be employed. These and other economic considerations will be taken up.

Hematite and Siderite.

The writer saw no evidence, other than local, of any oxidation to ferric oxide. So far as he is aware, prospecting has given no encouragement of a chance of finding hematite bodies. However, there would seem to be a chance for oxidation and concentration to take place in the troughs of the folds which occur in the rock over the area where the Upper Slaty beds outcrop east of the north-south fault running through Secs. 22 and 27. So far as the writer is aware, no explorations have been made in this part of the area. To investigate this possibility, drill holes should be sunk to the base of the formation. The only noteworthy iron-carbonate horizon is a thickness of about 5 feet at the top of the formation. From the vigorous effervescence with cold dilute acid, a large part of this rock is calcite. Therefore any iron mining must be in magnetite ore, unless future exploration discloses hematite in the region.

Magnetite Concentration Ore.

Magnetite Content.—The average chemical composition of a large part of the Gunflint iron formation is given by Van Hise and Leith as follows.[22]

SiO_2	60.51	K_2O	.00
Al_2O_3	1.20	H_2O	Small
Fe	25.22	P_2O_5	.05
MgO	.52	S	.59
CaO	.67	MnO_2	.92
Na_2O	.00		

A 3-foot layer at the base of the formation which contains over 55 per cent. in iron is mentioned. However, it must be kept in mind that the percentages of iron as given above are total iron. A process of magnetic concentration is designed to remove as far as practicable every mineral constituent excepting magnetite, from the concentrates. In the Gunflint formation, a considerable part of the rock consists of iron-bearing minerals other

[22] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 204.

than magnetite. The percentage of iron in these is rejected in magnetic concentration and goes into the tailings. Therefore, in considering the rock as to its availability for magnetic concentration, the iron in magnetite alone, conveniently referred to as "magnetic iron," is significant.

Inspection of the various horizons of the Gunflint formation shows that there are but two likely to prove of high enough magnetite content to be of value. By this is meant a horizon which will furnish one ton of magnetic concentrate of about 60 per cent. iron from three tons of rock or less. These horizons are the 5 to 15 foot thickness of magnetite rock in the Lower Cherty beds and the upper member of the Lower Slaty beds, about 45 feet in thickness.

Lower Cherty Beds.—The magnetite rich beds at the base of the Lower Cherty beds are admirably adapted to magnetic concentration. A sample of a 12-foot cliff of these beds in the NW. ¼ of Sec. 23, T. 65 N., R. 4 W. shows that 1.55 tons of rock, ground to 100 mesh, will make 1 ton of concentrate containing as follows:[23]

Soluble iron	59.22
Phosphorus	0.009
TiO_2	.03
S	0.00

Specimens of the same horizon from the stock pile at the Paulson mine, picked because of their high-grade appearance, were reported by the same laboratory as follows. One ton of concentrate of the following grade could be magnetically concentrated from 1.38 tons of rock after 100-mesh grinding:

Soluble iron	64.76
Phosphorus	0.009
TiO_2	.09
S	.21

The higher grade of concentrate in the latter is due to the coarser

[23] Results of a concentration test on a sample submitted to the Minnesota Mines Experiment Station, at the University.

crystallization nearer the gabbro. The higher content of titanium and sulphur have already been mentioned as being probable contributions from the gabbro. The grade of this horizon as an ore and the quality of concentrate produced from it are to be regarded favorably. The Paulson mine in Sec. 28 was a venture to mine this horizon, the intent being to ship a hand-sorted ore to Port Arthur. A railroad was built and considerable exploration done. The scheme failed and the rails were removed from the mine to North Lake, Ont.

From the standpoint of method of mining, there are three different areas in which this bed occurs. In parts of the northern halves of Secs. 22, 23, and 24, it lies exposed as a thin capping on the south slope of the granite hill. Its thickness as exposed varies from 0 to 12 feet. At best, it would make a low-faced quarry, and probably could never be regarded seriously as a mining proposition.

In the above-mentioned sections, the horizon dips under the upper beds at an angle of 7 to 12 degrees to the south. Terraces and minor folds make considerable local changes in this general dip. From surface geology, there appears to be a good chance of this horizon being within 50 feet of the surface in the valley in the NE. ¼ Sec. 26.

From the center of Sec. 27 westward the dip steepens rapidly, averaging 45° to the south. The thickness of the horizon for concentrating purposes varies from 5 to 15 feet in this vicinity, judging from the drill cores available for examination.

To summarize: There is a bed from 5 to 15 feet in thickness near the base of the Gunflint formation which will yield a high grade magnetic concentrate after being ground to 100 mesh, with a concentration ratio of about 1.5. The grade of concentrate obtained with the same fineness of grinding improves toward the western end of the district. Underground mining methods would be required to work the ore.

Lower Slaty Beds.—The other bed which might be a source of concentrating ore is the upper 45 feet of the Lower Slaty beds.

A sample[24] of this horizon from the SE. ¼ Sec. 22 shows that a little over two tons of rock, ground to 100 mesh yields one ton of magnetic concentrates, having the following grade:

Fe	47.32
P	0.028
TiO_2	0.16

A sample of 12 feet of the same beds, exposed in a cut a few rods east of the Paulson mine was reported as follows: A little more than two tons of rock, ground to 100 mesh, yields one ton of magnetic concentrates, assaying as follows:

Fe	48.79
P	0.017
TiO_2	0.21

Therefore, 100-mesh grinding is not fine enough, since the iron content of the concentrate is low. Finer grinding would raise the iron content, and probably lower the phosphorus content of the concentrates.

As in the case of the other magnetite rich horizon, the assays show the coarseness of grain and the TiO_2 content to increase near the gabbro.

The geological attitude of the beds would require underground mining methods. The dip is the same as the dip of the other magnetite bed described above. No considerable areas of this horizon are exposed, so it is not adapted to quarrying methods.

Other Economic Considerations.—Physically the rock is exceedingly hard and tough. Pore space is said to be less than 1 per cent. Exploration by diamond drilling is necessary to prove the continuity and grade of the horizons described above. The drilling need not be so closely spaced as in the outlining of hematite bodies of the Lake Superior region, for these are continuous beds, and the changes along any bed are gradual. Transportation would be about the same as on the Mesabi range; a haul of about 80 miles to Port Arthur, Ontario, thence by boat to the lower lake ports.

[24] Submitted to the Minnesota Mines Experiment Station for a concentration test.

Comparison with East Mesabi Magnetites.

As compared with the eastern Mesabi, the Gunflint area is much less favorable for mining and concentration. A comparison follows:

1. *Attitude of Beds.*—The beds over the greater part of the east Mesabi dip from 4 to 8 degrees to the south, outcropping in many places on a slope of 2 to 6 degrees in the same direction, which combination in many places allows the slope of the surface and the dip of the beds to be practically parallel, thus giving large surface outcrops of the various horizons. This makes quarrying a possibility. The Gunflint beds are steeper, and would require underground methods of mining.

2. *Thickness of Magnetite-rich Beds.*——On the east Mesabi there is a thickness of over 100 feet of beds which will make a 60 per cent. iron concentrate, with a concentration ratio of 2.5 after 100-mesh grinding. The greatest thickness observed in the Gunflint beds which would equal this in quality is 15 feet. On the east Mesabi there are other beds which would require extra fine grinding to produce a 60 per cent. concentrate, which are equal in thickness to the fine-grained magnetite-rich horizon in the Lower Slaty of the Gunflint, requiring the same or finer grinding.

3. *Grade of Ore.*—The 12 feet of Lower Cherty beds of the Gunflint sampled in Sec. 23 assayed 38.23 per cent. Fe in magnetite. This is better than any known similar thickness on the east Mesabi. The 45 feet of Lower Slaty beds of the Gunflint sampled in Sec. 22 ran 22.22 per cent. Fe in magnetite. There is a thickness of 100 feet on parts of the east Mesabi which will assay as well as that. Forty feet of the 100 feet of eastern Mesabi ore will approach 30 per cent. magnetic iron.

4. *Grade of Concentrate.*—The concentrate, with the same fineness of grinding, from the Lower Cherty magnetite of the Gunflint is equal to any from the Biwabik formation known to the writer. The concentrate from the 45 feet of Lower Slaty beds in the Gunflint is leaner than that from most of the horizons on the east Mesabi. Locally a high sulphur or titanium content may ruin the Gunflint formation as an iron ore.

5. *Tonnage of Ore.*—On the east Mesabi, exploration has shown that there is good concentrating ore in beds over 100 feet in thickness for two miles along the strike. Field mapping indicates that there is comparatively good material for a much greater distance.

In the Gunflint region the beds which are magnetite-bearing are about one half the thickness of the east Mesabi ore beds, and have a maximum extent of 9 miles along the strike. However, the steeper dip in the Gunflint, especially west of the Paulson mine, largely compensates for the thinness of the beds; a given 40-acre tract may have a greater tonnage of concentrating ore than any similar area on the greater part of the east Mesabi.

Inasmuch as 100-mesh material is too fine for present blast furnace practice, the concentrates of either the Gunflint or east Mesabi ores must be sintered or briquetted.

Summary.

The places where there are the best possibilities for hematite ore on the Gunflint have not yet been explored so far as the writer is aware. There are two horizons which are rich enough in magnetite to be interesting as furnishing possible concentrating ore, but several factors tend to make the costs of mining and concentrating higher than similar operations on the east Mesabi. Therefore, until it is proved on a commercial scale that concentrates from the east Mesabi magnetite can be sold at a profit, attempts to operate on the Gunflint would be premature.

PART III. THE APPLICATION OF DETAILED STRATIGRAPHY TO PRE-CAMBRIAN CORRELATION.

The value of detailed study of the lithology of pre-Cambrian formations in making correlation is worthy of mention. In 1885 Irving spoke of the proper employment of lithological character in making correlations in the pre-Cambrian, and predicted the increasing use of such evidence in the future.[25] Notable success

[25] Irving, R. D., "On the Classification of pre-Cambrian Formations," Seventh Ann. Rept. U. S. Geol. Survey (1885–1886), pp. 365–454, 1888.

in the detailed study of the beds of pre-Cambrian formations is apparent in the work of the past few years by Wolff of the Oliver Iron Mining Company, and the State Geological Surveys of Michigan, Wisconsin, and Minnesota. In the present instance, few geologists would demand any additional evidence of the identity of the Gunflint and the Biwabik formation, after having determined the characteristics and succession of the various beds of each formation and observed the points of similarity as listed above. One would be justified in correlating the two formations on the lithological similarity alone, in case the relations to other formations were not exposed. In fact, any contradictory evidence would be subjected to very severe scrutiny before it was admitted.

It is now known that the general fourfold division of the iron-bearing member of the Upper Huronian in Minnesota extends over a distance of about 170 miles along the strike. A hasty trip along the Ontario-Minnesota line, where the iron formation outcrops about 10 miles east of the area studied in detail, showed the presence of septaria in cherty concretions, and of the algal structures. Descriptions of the Loon Lake, Ontario, district, about 100 miles northeast of the Gunflint district, show an interbedded slate in the iron formation 25 to 30 feet in thickness and with about 50 feet of iron formation below and 300 above it.[26] This is just the position occupied by the "intermediate" slate of the Biwabik on the east Mesabi, and the Gunflint. Thus a detailed study of the Animikie beds of the Loon Lake district would be sure to show some of the features of the corresponding beds in Minnesota.

From the Upper Huronian of the Gunflint and Mesabi districts to the Upper Huronian of the Penokee-Gogebic of Wisconsin and Michigan, is about 120 miles. Since the Upper Huronian in Minnesota and Michigan are on the two opposite limbs of a syncline, the distance along the bedding is much greater, probably too great to expect to find any common features of bedding persisting across such a large area of deposition. However, it is

[26] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 207.

interesting to note the following features of the Ironwood formation of the Penokee Gogebic as described by Hotchkiss.[27]

1. Starting with a cherty horizon at the base, there is an alternation of cherty and slaty members.

2. A persistent bed of "gnarled concretionary jasper" which is red in some cases and light gray in others, is strongly suggestive of the lower algal chert of the east Mesabi.[28]

3. The top of the second cherty member is marked by a conglomerate as is the top of the Upper Cherty beds of the Biwabik and Gunflint.

4. In general the cherty members have "wavy" bedding planes and the slaty beds have parallel bedding planes. This is also true of the Biwabik and Gunflint formations.

The above likenesses are enough to cause one to look forward with interest to the time when geologists familiar with the details of one or another of the Upper Huronian formations of the Lake Superior region have the opportunity to study the others.

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MINNEAPOLIS, MINN.

[27] Hotchkiss, W. O., *op. cit.*, pp. 501–506.

[28] Broderick, T. M., "Detail Stratigraphy of the Biwabik Iron-bearing Formation, East Mesabi District, Minn.," ECON. GEOL., vol. 14, No. 6, p. 446, 1919.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE VEINS OF COBALT.

Sir:—When discussing or describing any of the ore bodies of northern Canada, authors are inclined to take liberties with the actions of the continental glaciers of the Glacial Period, and with the work of erosion which was done by them. The statement has often been made, and may perhaps be commonly believed, that thousands of feet of rock were ground down and worn away from the preëxisting rock surface by these glaciers. No reasonable evidence for such a statement has ever been offered, and Professor Fairchild and other geologists have long ago shown that the quantity of rock scraped from the general surface of the country by the overriding glaciers was comparatively small.

In a paper on "The Veins of Cobalt" in the March number, Vol. 15, of ECONOMIC GEOLOGY, Mr. Whitehead repeats the statement in a somewhat different way when he says "Oxidation . . . is all post-glacial" and "No remnants of the (pre-glacial) oxidation are at present found in the district." It is quite true that as a traveller wanders over the country he may observe that all the rocks exposed on hills, as well as on more or less extensive level or gently undulating plains, have been scored and planed off by glacial agencies down to the fresh unoxidized rock, and consequently he may jump to the conclusion that the glacier

planed off all the decomposed rock from the surface, whether that surface was high or low, quite irrespective of its relief. But such a traveller could not see the rocks in the bottoms of the valleys, for they are covered by superficial deposits of various kinds, and unfortunately if he came to the above conclusion, he would be ignoring the evidence that these particular rock surfaces might furnish.

But the prospecting and shallow mining operations that have been carried out during the past ten years, have shown that such a conclusion would have been incorrect. In many places in the bottoms of the valleys, and especially in those running transverse to the direction of glacial motion, and more especially on southern slopes protected from the impact of the glacier, the operations of prospecting, which consist of stripping off the superficial deposits in the search for mineral-bearing veins in the underlying rock, have shown the existence of much decomposed rock which clearly resulted from pre-glacial oxidation and decomposition. Such decomposed rock is always in hollows where it has been protected by the adjoining hills, and perhaps also by hard coverings of boulder-clay, from the scoring action of the glacier.

Typical examples of this pre-glacial decomposition may be seen on the south side of a hill on the property of the Anchorite Mine in Porcupine, Ontario, and in a somewhat similar situation on the property of the Otisse Mine in Matachewan, Ontario. But these are only outstanding instances, for similar occurrences of decomposed rock or vein matter, the result of pre-glacial oxidation, may be seen at many other places in northern Ontario where prospectors and miners have cleared away the superficial deposits from the surface of the underlying rocks.

It is possible that pre-glacial gravels may also be found under the glacial deposits in the bottoms of some of the deep and narrow transverse valleys, but as yet, so far as I know, no such gravels have been recognized.

J. B. TYRRELL.

CONFEDERATION LIFE CHAMBERS,
TORONTO, CANADA.

REVIEWS.

The Petroleum Handbook. By STEPHEN O. ANDROS. Pocket size, xiv + 206 pages, 48 illustrations. Price $2.00; also distributed gratis to new subscribers to *Oil News*. The Shaw Publishing Co., 910 S. Michigan Boulevard, Chicago, 1919.

This small volume termed a "handbook" is in reality a highly abridged treatise on the oil and gas industry. The book is divided into 8 chapters, the headings and number of pages given to each being as follows: I., Origin, accumulation, and occurrences, 26 pages; II., Exploration and drilling, 52 pages; III., Methods of petroleum refining, 30 pages; IV., Natural gas and its products, 31 pages; V., The shale oil industry, 9 pages; VI., Marketing of petroleum products, 14 pages; VII., Gasoline specifications, inspection laws, and marketing practices, 28 pages; and VIII., The economic utilization of petroleum, 16 pages. The author's attempt at all-inclusiveness within such a small volume is quite noteworthy. In this connection it may be pointed out that features of such incidental interest as the development of well drilling and the development of tank car transportation, which, according to the reviewer, are not pertinent to a handbook for current use, occupy seven pages of the text, whereas in contrast to these unessential historical treatments so important a feature as a geologic timetable is omitted.

In the preface the author states, "There is very little original matter in the book. The sources of compilation are numerous. . . ." This is strictly true, many portions being merely brief abstracts, and so brief are several of these that they would probably not be comprehensible to anyone unfamiliar with the phases treated. In this respect the author quite outdid his purpose, which, as stated in the preface, is to give the fundamentals of each phase of the industry by "eliminating descriptions unnecessary to a clear understanding of the various operations." Although the sources from which much of the information is obtained are listed, the method by which they are referred to in the text does not indicate the great extent to which they are drawn upon for material.

Numerous misstatements of fact were noted, of which the following are typical. On page 43 a bailer, such as is used in oil well drilling, is described as "A plain cylinder of light galvanized iron . . ." which is then augmented in the second sentence following by the statement, "The

average length of the bailer is about six feet . . . ." In nearly the same vein is the following on page 48: "Casing most commonly used in the Mid-Continent fields consists of sheet-iron pipe . . . ." The title to the last chapter "The economic utilization of petroleum" does not indicate the character of its content. On page 9 is the statement that "capillarity will draw the oil into the fine pores" which is then contradicted in the third sentence following by the assertion that gas and oil tend to move from shale to sandstone. On page 29 is a sketch bearing the title "Contour map of an area" which is quite erroneous inasmuch as the illustration is a structure contour map of a limestone bed.

Because of its highly abridged character which does not permit treatment adequate for a clear understanding of the subjects discussed, and because of its many inaccuracies, it seems rather doubtful to the reviewer that this volume will fill any general need in the oil and gas industry.

A. E. FATH.

SCIENTIFIC NOTES AND NEWS[1]

H. FOSTER BAIN has been making geological examinations in Yunnan, southern China.

A. E. FATH, of the U. S. Geological Survey, after a few weeks' field work in Creek County, Okla., is now in Wyoming with N. W. Bass and G. F. Moulton as field assistants in the examination of the oil and gas fields of Carbon County.

C. WILL WRIGHT, mining engineer, of Rome, Italy, recently visited United States, but has now returned to Italy.

G. C. MARTIN, of the U. S. Geological Survey, left Seattle July 8 for an investigation of the mineral resources of the lower Yukon and Kuskokwim regions, Alaska.

THE Rocky Mountain Division of the Roxana Petroleum Corporation has been reorganized as the Matador Petroleum Co., with headquarters in Cheyenne, Wyoming, and has a number of former Government men on its staff. Max W. Ball is manager; T. K. Harnsberger is chief geologist; John D. Northrop is chief of the Central Section, comprising Wyoming and Colorado; and E. L. Jones, Jr., is doing geologic work in southern Wyoming. The geologic staff of the division also includes Archer T. Spring, Justus H. Cline, H. M. Andreen, Robert W. Gibson, and Fred E. Wood, with Guy E. Miller, George V. Dunn, J. Alton Lauren, and Verne Austin as assistants.

J. S. DILLER, of the U. S. Geological Survey, who was seriously ill for a number of weeks at Miami, Ariz., has returned to Washington.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

EDWIN T. HODGE, mining engineer, has accepted the position of professor of economic geology at the University of Oregon.

W. C. ALDEN, of the U. S. Geological Survey, is spending the present field season in Montana in an investigation of the Quaternary and late Tertiary deposits of the Great Plains.

T. H. JENKS, mining engineer of Los Angeles, is spending the summer in Colorado, where he is doing professional work in Hinsdale County and other districts.

HARVEY BASSLER and J. B. Mertie, Jr., on furlough from the U. S. Geological Survey, are engaged in oil geology with Eugene Stebinger in Bolivia.

E. D. ELSTON, instructor in geology at Cornell University, has been appointed assistant professor of geology in Dartmouth College.

ADOLPH KNOPF is studying the Simon and Arabia mining districts, Nevada, for the U. S. Geological Survey.

A. C. BOYLE, JR., mining engineer, and professor at the University of Wyoming, has resigned from the University to accept the position of geologist with the Union Pacific R. R. Co., with headquarters in Omaha, Nebraska.

W. T. LEE, of the U. S. Geological Survey, who is completing field work on the coastal plain of Maryland and Virginia, has been making extensive observations of submerged topography by aëroplane with success.

E. G. ROBINSON, instructor in geology in the University of Nebraska, has been appointed to a similar position in Cornell University. He will spend the summer at field work in Montana.

WHITMAN CROSS, E. E. Larsen, and C. P. Ross of the U. S. Geological Survey, are in the southern part of the San Juan Region, Colorado, for the summer field season.

R. M. OVERBECK, of the U. S. Geological Survey, who has been engaged in petroleum geology in Bolivia, has returned to Washington.

W. S. W. KEW, on leave of absence from the U. S. Geological Survey, has left California for private work in Sonora, Mexico, where his address is Hermosillo.

WALLACE E. PRATT, chief geologist of the Humble Oil & Refining Company, has moved his office from Fort Worth, Texas, to Houston, Texas.

N. H. BOWEN has resigned his professorship in Queens University, Kingston, Canada, and has rejoined the staff of the Geophysical Laboratory of the Carnegie Institution of Washington.

L. F. NOBLE, who has been investigating the geologic occurrence of groundwater on the island of Hawaii for the U. S. Geological Survey, has returned to his home in California.

VAN H. MANNING, director of research for the American Petroleum Co., has his New York office at 19 West 44th Street.

E. C. HARDER, formerly of the U. S. Geological Survey, is doing work for the Aluminum Co. of America.

F. H. MOFFIT, with Herbert Insley as assistant, is investigating the possible occurrence of oil in the region west of Cook Inlet, Alaska, for the U. S. Geological Survey.

W. T. THOM, JR., of the U. S. Geological Survey, who has been doing relief work in Vienna, Austria, for the past six months, has returned to Washington.

LEWIS A. LEVENSALER, consulting mining engineer, announces opening of his offices at Suite 902, Hodge Building, Seattle, Washington.

D. D. SMYTHE, instructor in geology in Cornell University, is engaged in field work in Arizona this summer.

B. S. BUTLER has resigned from the U. S. Geological Survey, and will be associated with L. C. Graton in a study of the geologic problems of the Calumet and Hecla mines.

JAMES M. HILL has been assigned permanently to the San Francisco office of the U. S. Geological Survey. He will assist

in mineral resources work on the Pacific coast and be available for general geologic studies.

W. S. BAYLEY, of Urbana, Illinois, is at Murphy, N. C., continuing the investigation of the iron ores of North Carolina which was begun last summer by the U. S. Geological Survey in cooperation with the State Survey.

D. F. HEWETT, of the U. S. Geological Survey, returned to Washington from Cuba, June 7. On completion of private work, he spent six weeks on the manganese mines of eastern Cuba for the War Minerals Relief Commission.

WILLIAM YOUNG WESTERVELT, mining engineer, has moved his offices to Fifth Avenue Guaranty Building, 522 Fifth Ave., New York City.

R. A. F. PENROSE, JR., and A. R. Ronaghan were recently elected to the Board of Directors of the Chino Copper Co.

J. T. PARDEE, of the U. S. Geological Survey, will spend the summer on the glacial geology of western Montana and eastern Washington.

G. F. LOUGHLIN, of the U. S. Geological Survey, is engaged in field work in eastern Massachusetts.

D. E. WINCHESTER completed his report on the oil shales of the Rocky Mountain region for the U. S. Geological Survey and left July 8 for Denver, Colo., to direct oil-shale operations for the Carter Oil Co.

FRANK REEVES, J. M. Vetter, and Bruce White will constitute a field party in the prospective oil fields of central Montana for the U. S. Geological Survey.

A. C. TROWBRIDGE with W. D. Glock as assistant are studying the Coastal Plain deposits of southwest Texas for the U. S. Geological Survey.

H. BRINGS, of New York, is at present in France.

FRANK A. CRAMPTON and Theodore H. M. Crampton have reopened their office at 1247 Ocean Avenue, Santa Monica, California.

J. P. JOHNSON, formerly of the staff of the *South African Mining and Engineering Journal,* died recently at the age of thirty-eight years. Mr. Johnson was educated at the Royal School of Mines. In 1903 he went to South Africa where he was connected with various mines. He eventually established himself in Johannesburg as mining engineer and geologist.

ALFRED H. BROOKS, chief of the Alaska Division of the U. S. Geological Survey, accompanied Secretary Daniels and Secretary Payne and others on an inspection, beginning June 10, of the Government railroad in Alaska and the tributary coal fields. Later he will do geologic work in the Prince William Sound region.

D. H. NEWLAND has resigned as assistant state geologist of New York, and has taken a position with the Beaver Board Companies of Buffalo, New York, as field geologist and mining expert.

WARREN D. SMITH is on leave of absence from the University of Oregon to spend a year in geological work for the Philippine government. His present address is Chief of Division of Mines, Bureau of Science, Manila, P. I.

L. W. STEPHENSON has returned from Mexico and will be acting chief of the Coastal Plains section of the U. S. Geological Survey, during the absence of T. Wayland Vaughan who will attend the Pan-Pacific Scientific Congress in August and spend the rest of the summer in study and correlation of the marine Tertiary strata of the Pacific Coast.

H. G. FERGUSON, of the U. S. Geological Survey, spent the month of June completing his investigation of the ore deposits of Manhattan, Nevada.

EDWARD SAMPSON, recently appointed assistant geologist on the U. S. Geological Survey, is completing the work on the asbestos deposits of Arizona begun by J. S. Diller.

H. D. MISER, of the U. S. Geological Survey, will spend the month of July on the manganese deposits in the western part of the Valley of Virginia.

SIDNEY PAIGE will spend the summer in a study of the Homestake ore body in South Dakota.

F. C. SCHRADER, of the U. S. Geological Survey, spent June and July in field work on the mining districts of the Carson Sink quadrangle, Nevada.

A. C. SPENCER, assisted by G. C. Stevens, hydraulic engineer, recently investigated possible sources of additional water supply for the town of Strasburg, Va., at the foot of Massanutten Mountain.

JULIAN D. SEARS, of the U. S. Geological Survey, is continuing detailed study of the coal field at Gallup, N. Mex.

C. K. WENTWORTH, of the U. S. Geological Survey, assisted by J. B. Eby, is now engaged in field work on the coals of Wise County, Va.

C. E. SIEBENTHAL, of the U. S. Geological Survey, spent most of May and June visiting the zinc mines of Wisconsin, the lead mines of Missouri, and the fluorspar deposits of Illinois.

L. G. WESTGATE, of the U. S. Geological Survey, has sailed for Alaska and among other duties will investigate the recently discovered gold lodes of the Portland Canal region.

DAVID B. REGER, of Morgantown, W. Va., is on leave of absence from the West Virginia Geological Survey for the next four months and will devote that time to consulting work in petroleum and coal. He has just completed a month's trip to the prospective oil fields of Montana.

D. F. HIGGINS, geologist, expects to have his headquarters at Loveland, Colo., after September 1. He has just recovered from a serious attack of typhoid contracted during recent oil work in Egypt and Sinai.